

EVALUATING IRRIGATION AS A MINE WATER MANAGEMENT STRATEGY IN THE EASTERN BASIN OF THE WITWATERSRAND GOLDFIELDS

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Report to the Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND

Due to South Africa's mining legacy, large volumes of acid mine drainage (AMD) threaten the quality of water resources. Treatment technologies exist, but are expensive and energy-intensive. In the Witwatersrand Goldfields, three high-density sludge (HDS) water treatment facilities were established as emergency measures to neutralise large volumes of mining-influenced water in the Eastern, Central and Western Basins. These have been effective short-term measures; however, the salinity of the waters remains a concern, and sustainable long-term solutions are sought. Detailed assessments of the suitability of treated and partially treated goldfields waters were undertaken for all three of the Witwatersrand Basins, using a site-specific, risk-based irrigation water quality Decision Support System (DSS). These mining-influenced waters can be used productively and cost-effectively for irrigation, and livelihoods can be created. It was, therefore, deemed worthwhile to address any potential concerns associated with this option.

Of the three basins, the Eastern Basin waters were of the best quality for irrigation, with the greatest volume treated (80 ML/day), and the water source was located close to agricultural areas. It was for these reasons that the project team focused on this basin: to demonstrate that irrigation can be successful with untreated mining-influenced waters on limed soil or with HDS-treated mining-influenced waters, and to develop a process for assessing the establishment of large-scale irrigation with mining-influenced waters with acceptable environmental impact. Additionally, the socioeconomic aspects of commercial-scale mine water irrigation were investigated.

AIMS

The following were the aims of the project:

- i. To demonstrate irrigation with untreated and partially treated mining-influenced water in the Eastern Basin
- ii. To identify key considerations for locating large-scale mine water irrigation schemes in the Eastern Basin
- iii. To identify monitoring requirements and thresholds for action for mine water irrigation schemes in the Eastern Basin
- iv. To model field-scale water and salt balances of different cropping systems irrigated with Eastern Basin mine waters
- v. To quantify the socioeconomic sustainability of irrigation with Eastern Basin mine water

There were three main components to the study that required a multi-disciplinary approach to address the aims:

1. Crop responses to irrigation with Gold Mine Water from the Witwatersrand Basins

This component of the study aimed to evaluate crop responses to irrigation using mining-influenced water from the Witwatersrand Goldfields. Glasshouse pot trials were conducted to assess the productivity of crops irrigated with mine water from the Witwatersrand Goldfields. Biomass production and grain/seed yield were used as measures of productivity, and grain/seed was analysed for trace elements considered as potential contaminants in food.

The glasshouse pot trials demonstrated that crops can be successfully irrigated with treated mine water, including salt-sensitive crops. Generally, irrigation with mine waters has no significant effect on the biomass production and yield of the assessed crops. The results also demonstrated that untreated mine waters can be used for irrigation if soils are strategically limed. Variability in crop responses to irrigation with untreated mine water highlighted the importance of crop selection, with some crops being more sensitive to it than others. From a productivity aspect, both treated and untreated mine waters from the Witwatersrand Goldfields can be used for irrigation, provided farmers commit to liming their soils.

Consumption safety was an important consideration in this work due to potential concerns about irrigation with water containing trace elements. Plant material was analysed for trace elements considered as potential contaminants in food; however, the absence of harmonised commodity-specific threshold values for some trace elements and technical limitations in analysing plant material, particularly the very low detection limits required, made it difficult to conclude the consumption safety assessment. Within the scope, timeframe, and resources of the project, these uncertainties could not be further resolved.

2. Assessment of Potential Impacts of Large-Scale Mine Water Irrigation on The Groundwater Environment and Receiving Surface Water Bodies

This component of the study aimed to assess potential influences on the groundwater environment and receiving surface water bodies (via base flow), thereby aiding in identifying monitoring requirements and action thresholds for mine water irrigation schemes in the Eastern Basin. The potential impacts of mine water irrigation on groundwater and receiving surface water bodies were assessed by modelling salt and water balances and performing predictive hydrogeological simulations. This part of the project was undertaken in three phases:

- Phase 1: Conceptual site model development
- Phase 2: Numerical groundwater model development
- Phase 3: Predictive model simulations

While irrigation with mine waters is expected to have some impacts on ground and surface water, results from various worst-case groundwater modelling scenarios suggest that irrigation with Eastern Basin mine water can be sustained in the medium to long term with acceptable impacts on ground and surface water. Location and distribution of irrigated areas were identified as key factors in ensuring the sustainability of this practice and ensuring impacts remain acceptable. The modelling results suggest that, for mine water irrigation to be sustainable, irrigated areas should ideally be located far from watercourses and spread across the landscape rather than concentrated in one location to minimise impacts.

3. Economic Aspects of Large-Scale Mine Water Irrigation in The Eastern Basin

This component of the study aimed to investigate the economic sustainability, potential socioeconomic impacts, and scalability of mine water irrigation in the Witwatersrand Goldfields, specifically the Eastern Basin. This part of the project was also undertaken in three phases:

- Phase 1: Market Analysis
- Phase 2: Development of an actual farm model
- Phase 3: Analysis of economic sustainability, socioeconomic impacts and scalability of mine water irrigation

The economic assessments indicated that irrigation with either treated or untreated water from the Eastern plant is economically viable, with the minimum individual farm area of 120 ha double-cropped as the best opportunity. Cash flow can be an issue due to the capital required for irrigation infrastructure and the cost of water, which, while acceptable for the current projection, remains a key concern. Considering the two area-based scenarios (2400-6000 ha), 20-50 farms could potentially be intensified with mine water irrigation, creating at least 3 jobs per farm. However, establishing emerging commercial farmers is likely to have a greater socioeconomic impact if land ownership is not a constraint.

Key Considerations

Irrigation with mine-influenced waters is a mine water management option worthy of serious consideration in the Goldfields of South Africa. This study has developed an approach to assess the feasibility of mine water irrigation and guide the process of rollout, and identified the following factors as being key to the planning and management of mine water irrigation schemes:

- Water quality and quantity
- Crop selection
- Total irrigation area
- Management of excess mine water
- Infrastructure
- Land availability and ownership
- Water costing
- Siting of irrigation schemes

Conclusion

Irrigation offers a mine water management option that will support water security and agricultural productivity. Assessments conducted using the Eastern Basin as a model site indicate that crops can successfully be irrigated with treated and untreated mine water, with acceptable environmental impacts and socioeconomic benefits. There are many ways to approach a large-scale irrigation rollout; however, in-depth, site-specific studies will be required to develop optimal solutions.

Recommendations for further research

Although this study was extensive and successfully addressed the aims set out, several limitations were identified that could not be addressed within the scope and timeframe allocated. The following research is therefore recommended to address these limitations:

- Understanding the hydrogeology of the underground mine workings in relation to storage capacity, uncontrolled mine water discharge points
- Quantifying the assimilative capacity of aquifers and receiving surface water bodies
- A detailed engineering study on water storage and conveyance, as well as the associated infrastructure costs and risks
- Field trials to validate the pot trial results and further investigate crop responses to sustained irrigation with this water, the consumption safety of produce, and the effects on soil quality over time.

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ACRONYMS & ABBREVIATIONS

AMD	Acid mine drainage
BFAP	Bureau of Food and Agricultural Policy
CaCO ₃	Limestone
CaSO ₄	Gypsum
CB	Central Basin
CCE	Calcium carbonate equivalent
DAFF	Department of Agriculture, Forestry and Fisheries
DWS	Department of Water and Sanitation
EB	Eastern Basin
EC	Electrical conductivity
EC _e	Soil saturated paste electrical conductivity
ECL	Environmental critical level
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organisation
GRI	Germination rate index
GP	Germination percentage
HDS	High-density sludge
ICP-AES	Inductively coupled plasma atomic emission spectroscopy
ICP-OES	Inductively coupled plasma optical emission spectrometry
LSD	Least significant difference
IrrigWQ DSS	Irrigation Water Quality Decision Support System
MGT	Mean germination time
TDM	Total dry mass
TDS	Total dissolved solids
UP	University of Pretoria
VRS	Vaal River System
WB	Western Basin
WHO	World Health Organisation
WRC	Water Research Commission
WS	Weather station
WTP	Water treatment plant

INTRODUCTION

Due to South Africa's mining legacy, large volumes of acid mine drainage (AMD) threaten the quality of water resources. Often, when mines close, active pumping and water treatment cease, resulting in flooding and eventual decant with potentially serious downstream consequences. Such a decant risk was identified across the Witwatersrand Goldfields, which is divided into three main basins: the Eastern, Central, and Western Basins. When mine water decanted from the Western Basin in 2002 and spilt into a nearby nature reserve, a sense of urgency was created. This, together with the risk of flooding infrastructure, motivated the introduction of the "short-term" solution. Decisions had to be made on pumping water from the basins and keeping levels below "Environmental Critical Levels" to protect the environment and infrastructure (DWS, 2010). High-Density Sludge (HDS) plants were built in the Eastern Basin (80 ML/d), Central Basin (72 ML/d) and Western Basin (33 ML/d), the so-called "Short-term solution".

Treatment technologies exist, but are expensive and energy-intensive. In the Witwatersrand Goldfields, three high-density sludge water treatment facilities were established as an emergency measure to neutralise large volumes of AMD in the Eastern, Central and Western Basins. These have been effective short-term measures, but sustainable long-term solutions are sought. Goldfields mine waters contribute to the salinity of the Vaal River System (VRS). However, since the volumes are relatively small, 185 Megalitres per day (ML/d), the focus is on keeping as much as possible out of the VRS, and not on reclaiming the water for other uses. This creates the opportunity to consider irrigation (a consumptive water use) as a potential solution.

Much local research has shown that irrigation with circum-neutral, gypsiferous waters can be successfully undertaken. The advantage of irrigation with waters rich in calcium and sulphate is that this sparingly soluble salt precipitates in the root zone upon concentration through root water uptake. This gypsum precipitation is not deleterious to the soil, and the capacity to precipitate is not finite. Although successful irrigation with circum-neutral, calcium and sulphate-rich waters has been demonstrated in the Coalfields, several concerns arose when irrigation with mine water was suggested as a potential long-term option in the Witwatersrand Goldfields. These were as follows:

- Are these waters suitable for sustained irrigation?
- What would the environmental impact be?
- Is sufficient irrigable land available in the built-up Witwatersrand region, and will it be possible to convey mine waters to it?
- Will farmers be willing to irrigate with these waters?
- What are the costs/benefits of this option?

Three key research components were identified from the concerns raised regarding irrigation with mine waters, which required an interdisciplinary approach. These components were agronomic, hydrogeological, and economic. The agronomic component of the study aimed to demonstrate the productivity and evaluate the sustainability of mine water irrigation, and the main responsible team was the University of Pretoria, made up of agronomists. The hydrogeological component aimed to assess the impact of mine water irrigation on groundwater and receiving surface water bodies. The team responsible for this component was Delta H, made up of hydrogeologists. The economic component aimed to investigate the economic aspects of mine water irrigation, and the main responsible team was the Bureau for Food and Agricultural Policy (BFAP), composed of agricultural economists.

This research study sought to address the concerns raised when irrigation was proposed as a mine water management option in the Witwatersrand Goldfields, and the following study aims were identified:

- i. To demonstrate irrigation with untreated and partially treated mining-influenced water in the Eastern Basin
- ii. To identify key considerations for locating large-scale mine water irrigation schemes in the Eastern Basin
- iii. To identify monitoring requirements and thresholds for action for mine water irrigation schemes in the Eastern Basin
- iv. To model field-scale water and salt balances of different cropping systems irrigated with Eastern Basin mine waters
- v. To quantify the socioeconomic sustainability of irrigation with Eastern Basin mine water

This report presents the outcomes of the research conducted to achieve the study's aims. The next section will discuss the rationale and provide a contextual overview of the study.

CHAPTER 1: STUDY RATIONALE AND CONTEXTUAL OVERVIEW

1.1 MINE WATER IN THE WITWATERSRAND GOLDFIELDS

Many deep underground mines in the Witwatersrand Goldfields closed in the late 1990s and early 2000s. As a result, water began to accumulate in the mine workings, generating acid mine drainage (AMD) as it reacted with pyrite. The reaction between pyrite and water in an oxidising environment produces sulphuric acid and iron hydroxides. The sulphuric acid formed dissolves minerals in the geologic material it comes into contact with, releasing metals and other elements into the water. This process produces acidic and mineralised water, typically with high concentrations of SO_4 , Fe, Al, and Mn, together with increased levels of potentially toxic metals, including Cd, Co, Cu, Mo and Zn (Akciil and Koldas, 2006, Baloyi, et al., 2024, Simate and Ndlovu, 2014).

In 2010, three of the basins in the Witwatersrand goldfields – the Eastern, Central, and Western Basins were identified as posing the greatest AMD discharge risk. This was after AMD from the Western Basin discharged into a nearby nature reserve, making national news and prompting emergency interventions (Coetzee, 2010). These interventions included setting environmental critical levels (ECLs), which are threshold water levels that must be maintained in underground mine workings to prevent AMD discharge. In addition, three high-density sludge (HDS) treatment plants, one in each basin, were constructed to pump and treat approximately 185 ML/day of AMD from the Witwatersrand basins.

A major concern with the AMD from the Witwatersrand basins was the acidity and the high concentration of sulphates, total dissolved solids and trace elements (Coetzee, 2010). Target salinities of 600 mg/L have proved difficult to meet, necessitating the unsustainable release of 5-11 units of expensive Lesotho Highlands water for dilution, for each unit of AMD entering the system. This could lead to a surplus of water in the lower catchment where it is not needed. HDS is a relatively inexpensive water treatment option that neutralises water acidity and reduces trace element levels. However, the salt load to the Vaal River System remains unacceptable, and longer-term solutions are being sought. Reverse Osmosis (RO) was mooted as the preferred long-term solution, as it is a proven technology that has been successfully demonstrated. However, it has high capital and running costs and is energy-intensive.

In the Witwatersrand Basins, the volume of AMD treated is relatively small compared to that required by the local water utility, Rand Water. Treating this mining-influenced water to potable standards with RO, therefore, will not make a substantial contribution to Gauteng's fresh water supply. It will also be expensive and energy-intensive to treat, and there may be resistance to domestic consumption of purified mine water. Due to the prevalence of abandoned and ownerless mines, the management of this mine water is a taxpayer liability. The key water management requirement in the Witwatersrand region is to keep as much salt as possible out of the Vaal River. This makes irrigation, a consumptive use of water, with the opportunity to precipitate gypsum in the soil, worth considering (Annandale, et al., 1999). Apart from creating livelihoods, irrigation should also be cost-effective. In addition, commercial irrigation with water from the Vaal System was curtailed several years ago, as it was not considered a priority water use. Hence, there is clear motivation to use alternative water sources (greywater, sewage, industrial, and mine water) for irrigation.

1.2 FITNESS-FOR-USE OF WITWATERSRAND GOLD MINE WATERS FOR IRRIGATION

In 2018, the Water Research Commission assembled a Team of Experts to provide recommendations for mine water management in the Witwatersrand Goldfields. As part of this exercise, the University of Pretoria was requested to assess the feasibility of irrigating with untreated and HDS-treated mine waters from the Eastern, Central and Western Basins. These assessments aimed to address questions that arise when irrigation is proposed as an option for mine water management. The team used the limited data available to them at the time to calculate worst-case scenarios and simulate long-term irrigation using water from the three basins. Once complete, the work was packaged into a manuscript, and after several iterations, the manuscript was accepted for publication in the journal titled *Mine Water and the Environment* (Annandale, et al., 2023). A summary of the findings is presented below; the full manuscript can be accessed at <https://doi.org/10.1007/s10230-023-00961-3>.

1.2.1 Water quality

Data for untreated and treated mine-influenced waters from the goldfields were supplied by the Department of Water and Sanitation (DWS) (Personal communication, Mr Bashan Govender and Mr Divan van Niekerk). This data was collated to determine the 95th percentile of constituent concentrations and the 5th percentile for pH, to provide a “worst-case” assessment of the suitability of these waters for irrigation. These water qualities are given in Table 1.1. Since the water quality data were collected through random sampling, the reported 95th percentile values for the individual constituents of the AMD- and HDS-treated water pairs do not always follow a consistent pattern and may, for example, not exhibit a tight charge balance between anions and cations. The calcium values of the HDS-treated waters of the Eastern Basin are, for example, less than those of the AMD waters. However, the aim was to undertake an initial assessment, using conservative assumptions, of the potential of these waters for irrigation, so such discrepancies are unlikely to affect the conclusions drawn at the end of this study.

Table 1.1 Worst-case water qualities used to assess suitability for irrigation for the EB (Eastern Basin), CB (Central Basin), and WB (Western Basin). AMD denotes untreated water, HDS is treated water, and ND is no data

Constituent	EB AMD	EB HDS	CB AMD	CB HDS	WB AMD	WB HDS
pH	6.2	7.2	5.8	8.4	5.8	8.6
EC mS/m	300	260	490	403	350	385
Ca mg/L	370	340	517	668	520	650
Mg mg/L	120	95	251	178	130	90
Na mg/L	200	206	207	192	110	170
SO ₄ mg/L	1600	1660	3760	2710	2200	2400
Cl mg/L	120	120	96	97	80	85
HCO ₃ mg/L	0.1	166	0.1	0.1	0.1	50
SAR (mmol/L) ^{1/2}	2.3	2.6	1.9	1.7	1.1	1.6
Fe mg/L	100	0.2	610	0.13	120	1.3
Mn mg/L	0.4	0.1	25	1.5	30	3.1
Al mg/L	ND	ND	144	0.05	ND	ND
Ni mg/L	ND	ND	ND	0.02	3	0.05
B mg/L	ND	ND	ND	ND	1.3	1.6
F mg/L	ND	ND	ND	ND	1.3	1.4
U µg/L	ND	ND	ND	5	86	29

1.2.2 Model description

A site-specific, risk-based irrigation water quality Decision Support System (IrrigWQ DSS) developed by du Plessis, et al. (2023) was used to determine if there are cropping systems for which these waters may be deemed suitable for irrigation in the Goldfields region. The DSS can be downloaded free of charge from <https://www.wateradmin.co.za/sawqi.html>.

The DSS can assess the implications of irrigating with a range of waters, including mining-influenced waters, on soil and crop resources, as well as on irrigation equipment. This is done through the assessment of suitability indicators, each divided into one of four fitness-for-use (FFU) classes, which are colour-coded to make the output intuitive and presented as 'ideal', 'acceptable', 'tolerable' or 'unacceptable'.

The DSS operates at two tiers. Tier 1 simulations require only water-quality data; conservative assumptions are used to assess water quality suitability for irrigation. The soil-crop-water interactions are calculated using an idealised soil profile with four layers and the assumption that crops withdraw 40% of the water they require from the top layer, with the percentage of water withdrawn by crops decreasing by 10% for each lower layer (Rhoades, 1982, Pratt and Suarez, 1990). The levels of constituents in the irrigation water were used to calculate the steady state (or equilibrium) concentrations of soluble constituents in each layer. A conservative 10% leaching fraction was assumed for the profile, with immediate percolation and leaching of dissolved salts when the profile exceeds field capacity.

Tier 2 allows the user to select site-specific conditions and assess how implementing specific management options, such as different crop selections or leaching fractions, affects the fitness-for-irrigation of a given water. A simplified version of the dynamic soil water balance (SWB) model is used to perform the Tier 2 calculations (Annandale, et al., 1999, Annandale, et al., 2001, Annandale, et al., 2011, Singels, et al., 2010). This includes a simplified chemical equilibrium model that simulates gypsum solution and precipitation reactions (Robbins, 1991). Simulations are run for a minimum of 10 years, but typically for 45 years, to better assess risk and sustainability using long-term data from an appropriate user-selectable weather station in close proximity to the irrigated area. The model output presents water and salt balances of the user-selected crop or crops and assesses the suitability of the irrigation source for their production.

1.2.3 Modelling parameters

The DSS was used to run several site-specific (Tier 2) 45-year simulations, using the worst-case water quality for each basin, both before and after treatment. A representative weather station with 50 years of daily temperature and precipitation data, located close to each basin, was selected. Figure 1.1 shows the location of the Witwatersrand Goldfields, the river system, the HDS treatment plants, the Lesotho Highlands water supply, weather stations, and land types in the region. A summary of the weather data obtained from the selected weather stations is presented in Table 1.2.

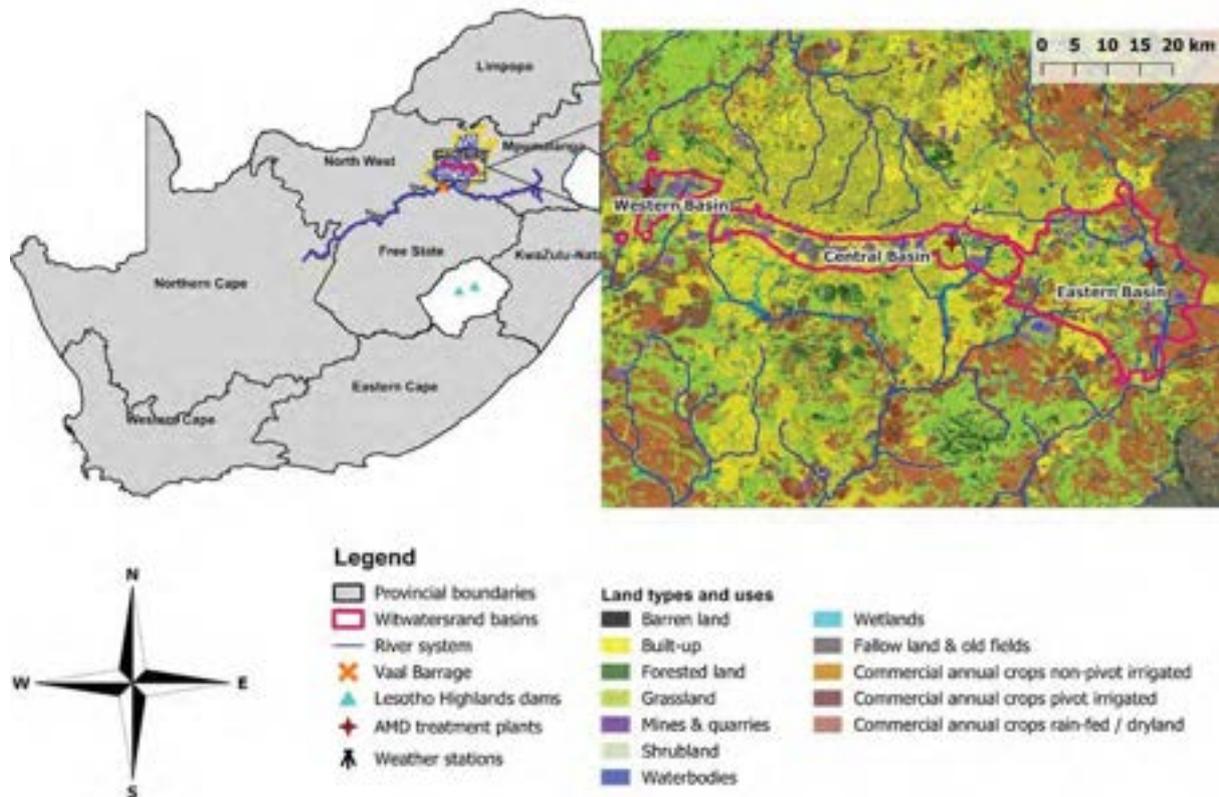


Figure 1.1 Map of the Witwatersrand Goldfields showing the HDS treatment plants and land types in the region.

Table 1.2 Weather data summary from representative weather stations used in the simulations. EB (Eastern Basin), CB (Central Basin) and WB (Western Basin)

Parameter	EB and CB	WB
Weather station (WS)	Germiston-Rand Airport	Krugersdorp-West
Weather station coordinates	26.15° S, 28.25° E	26.10° S, 27.75° E
Weather station elevation (m)	1660	1743
Minimum temperature (°C)	-1.8	-4.4
Maximum temperature (°C)	34	33
Mean annual precipitation (mm)	692	682

A virtual sprinkler irrigation system was selected to simulate foliage wetting and assess expected leaf scorch. Irrigations were triggered when the model detected a root zone deficit to field capacity in excess of 30 mm, with the irrigation amount calculated to leave 10 mm of 'room for rain'. Therefore, any leaching would occur due to the summer rainfall, and not through purposeful over-irrigation for salt management. Maize monocropping in summer, or a summer crop rotation of soybean and a small grain, such as wheat or sown rye, in winter, were selected as cropping systems worth investigating. Crop selection for irrigation with poor-quality water is critical, as crops vary widely in their tolerance to salinity and other constituents of irrigation water.

1.2.4 Key Findings and Recommendations

Except for the untreated Central Basin Water, which was more saline, the effects of most of the mine waters on rootzone salinity were predicted to be acceptable, with minimal effects on crop yield expected. The Eastern Basin waters were predicted to pose a soil-permeability risk occasionally; however, this risk can be mitigated by adopting appropriate management practices. Several trace elements were identified as potentially concerning in untreated waters; however, most of these were addressed in HDS-treated mine water. All untreated waters were predicted to pose an unacceptable corrosion risk to the irrigation equipment. HDS treatment reduces the corrosivity and the risk of equipment clogging caused by trace element concentrations. Since the water is gypsiferous, double cropping was predicted to precipitate more than a third of the dissolved salts as gypsum in the soil profile, thereby reducing the salt load to the water environment. The Goldfields waters are not very acidic, and the FFU assessments indicated it should be feasible to utilise even the untreated water for irrigation, especially if growers commit to applying limestone to their fields. It was therefore recommended that an attempt be made to address any potential concerns with using irrigation to manage these waters.

1.3 STUDY AREA SELECTION RATIONALE

Due to the project's limited budget, the team proposed primarily focusing on one of the basins to demonstrate that irrigation can be successful with untreated or neutralised mining-influenced waters, and to develop the process to follow for large-scale irrigation with mining-influenced waters to minimise environmental impact. Assessments conducted by the team indicated that the greatest opportunity for success with mine water irrigation would be in the Eastern Basin. Firstly, the water quality in the Eastern Basin appeared to be the most suitable for irrigation of the three basins, as the salinity of Central Basin water was quite high, and there was concern over Uranium and possibly Boron in the Western Basin waters. Even untreated Eastern Basin water seemed suitable for irrigation if farmers do not use it with drip irrigation (high Fe levels can cause dripper clogging), and if the slight corrosion risk of untreated water can be tolerated. Secondly, the Eastern Basin treats more water than the other two, more than 40% of the goldfields water reports to the Eastern Basin HDS plant (80-100 ML/d). Thirdly, the Eastern Basin has agricultural areas in close proximity to the HDS plant, making it more likely that water can be delivered to potential irrigators at a lower cost (Figure 1.1).

1.4 REGIONAL CONTEXT

1.4.1 Locality

The Eastern Basin Acid Mine Drainage Treatment Plant is located on the East Rand near Strubenvale in Gauteng. The area to the east of the study site is mainly farmland and fields, whilst to the west it is mainly urban development. This is also indicated by a denser road and rail network to the west in comparison to the east of the study site (Figure 1.2).

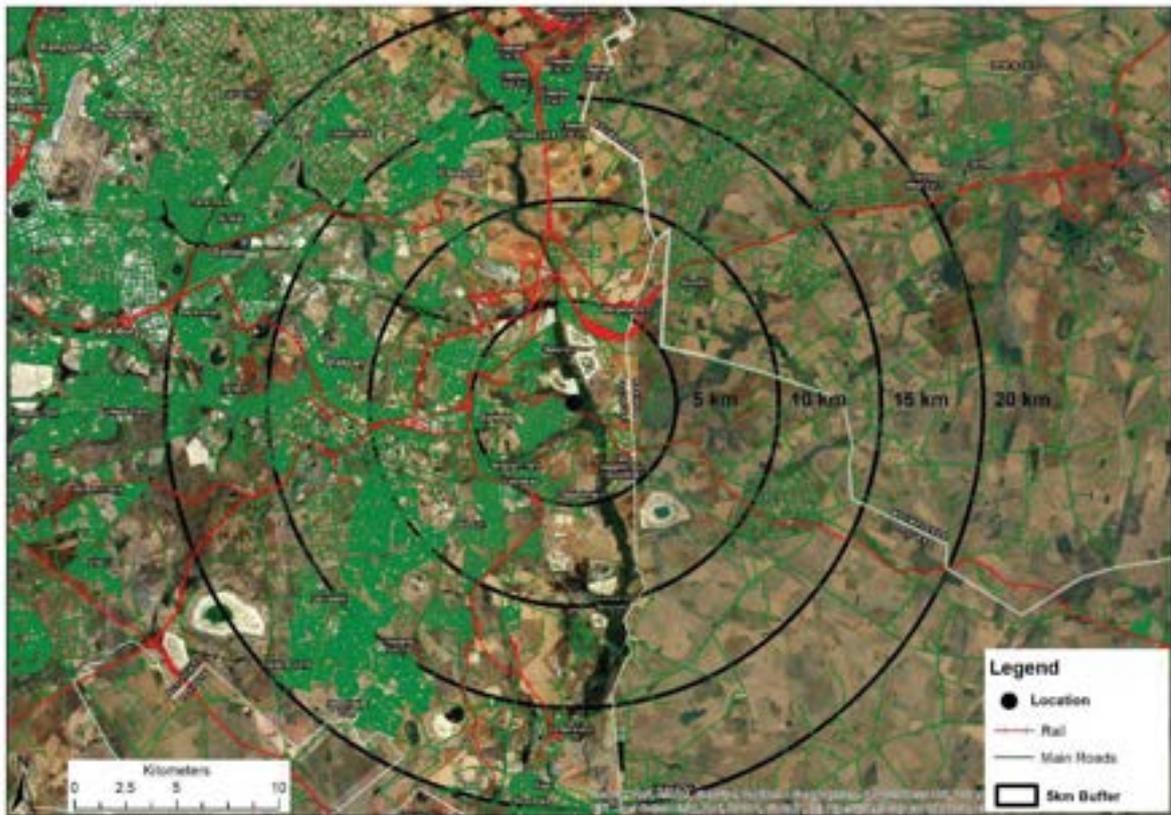


Figure 1.2 Location with a 20 km buffer with road and rail infrastructure and satellite imagery as background

1.4.2 Land availability and agricultural activity

To assess land availability, existing cultivated land was identified and used as a baseline for quantifying the area of land that can potentially be irrigated with the mine waters. That is, all cultivated land is considered potentially irrigable given appropriate infrastructure investment. The initial assessment area covered a 20 km radius and was divided into buffer zones of 5 km increments, with the study site as the midpoint (Figure 1.3). Potential available crop land was calculated using historic and current land cover data from 1998 to 2020 (DFFE, 2021) and field crop boundary delineations (Figure 1.3 and Figure 1.4). Table 2.3 presents the land cover/use in hectares within the 5–, 10–, 15– and 20-kilometre buffer zones over time from 1998 to 2020. Even though the methodology for land cover classification has changed somewhat over time, there is a clear trend of increased urban area and decreased cropland. Furthermore, there was also a marked increase in irrigation from 2013. The total agricultural cash crop production area in 2020 was just over 40 000 ha (annual rainfed and pivot irrigated cash crop production land) within the 20 km buffer.



Figure 1.3 Buffers from 5 to 20 km with the WTP as the midpoint and field crop boundaries

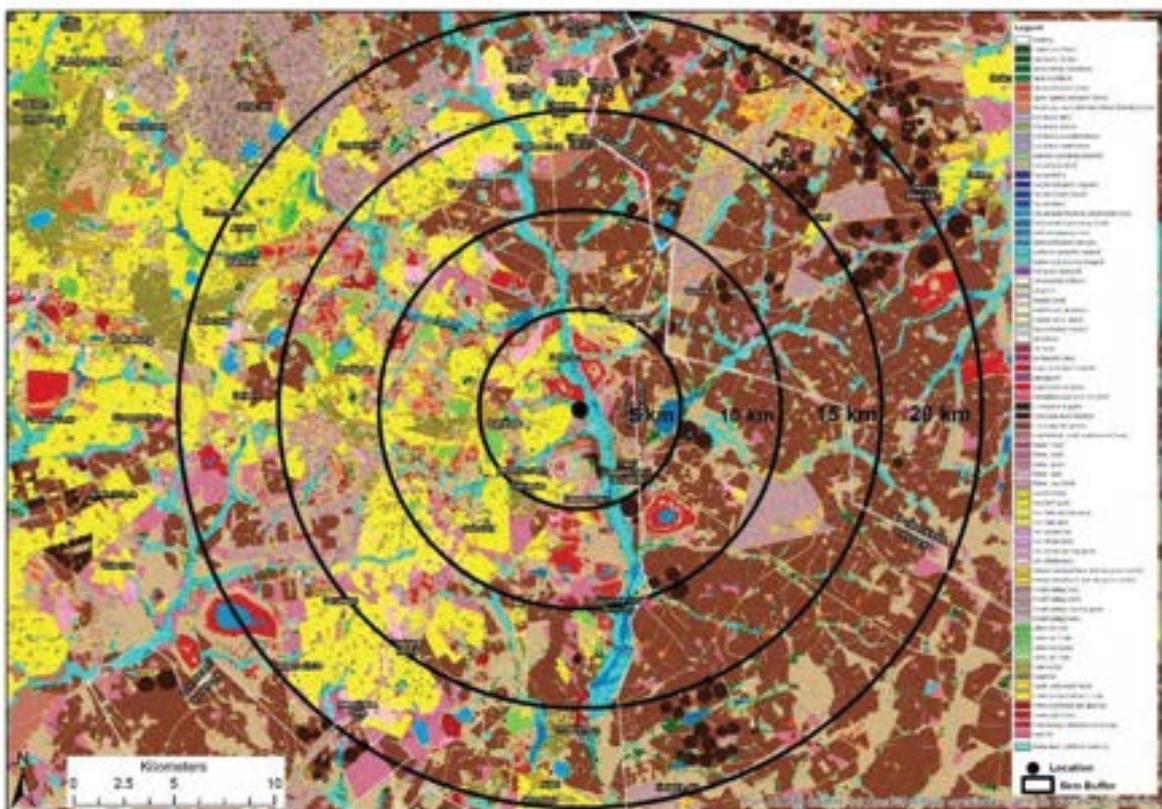


Figure 1.4 Buffers of 5 to 20 km around the WTP with the 2020 land cover as background

Table 1.3 Areas (ha) of different land covers within the 5 to 20 km buffer zones for the years 1998 to 2020

Year	Land use	5 km	10 km	15 km	20 km
2020	Crops Dryland	1 031	7 533	21 772	38 754
	Crops Irrigated	96	565	844	2 976
	Grassland & Fallow	2 533	10 024	19 456	35 122
	Urban Areas	2 185	6 795	17 327	31 057
	Mining, Landfill & Sewage	736	2 445	3 625	5 477
	Natural Water Bodies & Wetlands	820	2 235	4 320	6 675
	Forest, Wood & Shrubland	394	1 597	2 927	4 786
	Barren Land	60	223	414	817
2018	Crops Dryland	939	7 170	21 140	37 733
	Crops Irrigated	95	605	885	2 923
	Grassland & Fallow	2 640	10 259	19 990	36 362
	Urban Areas	2 201	6 920	17 488	31 391
	Mining, Landfill & Sewage	750	2 650	3 906	5 881
	Natural Water Bodies & Wetlands	887	2 394	4 580	6 886
	Forest, Wood & Shrubland	262	1 127	2 126	3 416
	Barren Land	81	291	572	1 073
2013	Crops Dryland	1 031	8 112	23 276	41 821
	Crops Irrigated	93	588	860	2 822
	Grassland & Fallow	2 664	9 735	18 849	33 933
	Urban Areas	1 834	5 809	15 038	26 835
	Mining, Landfill & Sewage	388	1 583	2 346	3 438
	Natural Water Bodies & Wetlands	1 084	2 622	4 592	6 939
	Forest, Wood & Shrubland	719	2 813	5 446	9 450
	Barren Land	40	155	277	424
2000	Crops Dryland	1 188	7 589	20 546	35 898
	Crops Irrigated	20	252	365	1 716
	Grassland & Fallow	2 300	9 352	20 550	40 143
	Urban Areas	1 867	6 248	14 900	25 427
	Mining, Landfill & Sewage	909	3 130	752	6 508
	Natural Water Bodies & Wetlands	1 223	3 402	6 537	10 379
	Forest, Wood & Shrubland	347	1 435	3 029	5 570
	Barren Land	0	7	21	21
1990	Crops Dryland	1 570	9 706	27 171	50 426
	Crops Irrigated	5	246	321	499
	Grassland & Fallow	1 931	7 822	16 327	30 619
	Urban Areas	1 746	5 643	13 518	24 209
	Mining, Landfill & Sewage	690	2 508	3 620	4 873
	Natural Water Bodies & Wetlands	951	2 392	4 135	6 224
	Forest, Wood & Shrubland	913	2 938	5 339	8 496
	Barren Land	48	162	252	315

From a hydrogeological perspective, the use of mining-influenced waters for irrigation requires some technical considerations, such as the potential for constituents to move into groundwater and surface water courses. To circumvent this, fields located above dolomitic aquifers were excluded. In addition, fields in close proximity to streams and rivers, and their sources, that could be impacted by the water source within 5 years (based on Delta-H simulation analysis) were also excluded. Figure 1.5. illustrates the cultivated fields in yellow, dolomitic aquifers in red/pink, and 5-year contamination potential in rivers and their sources in blue and green. All three delineations are classified as “no-go” zones. Table 1.4 presents the total field crop area of fields that overlie dolomitic aquifers, as well as streams and rivers, and their origins. Some fields cover more than one of these limitations; therefore, the total excluded area is less than the sum of the “no-go” classifications below.

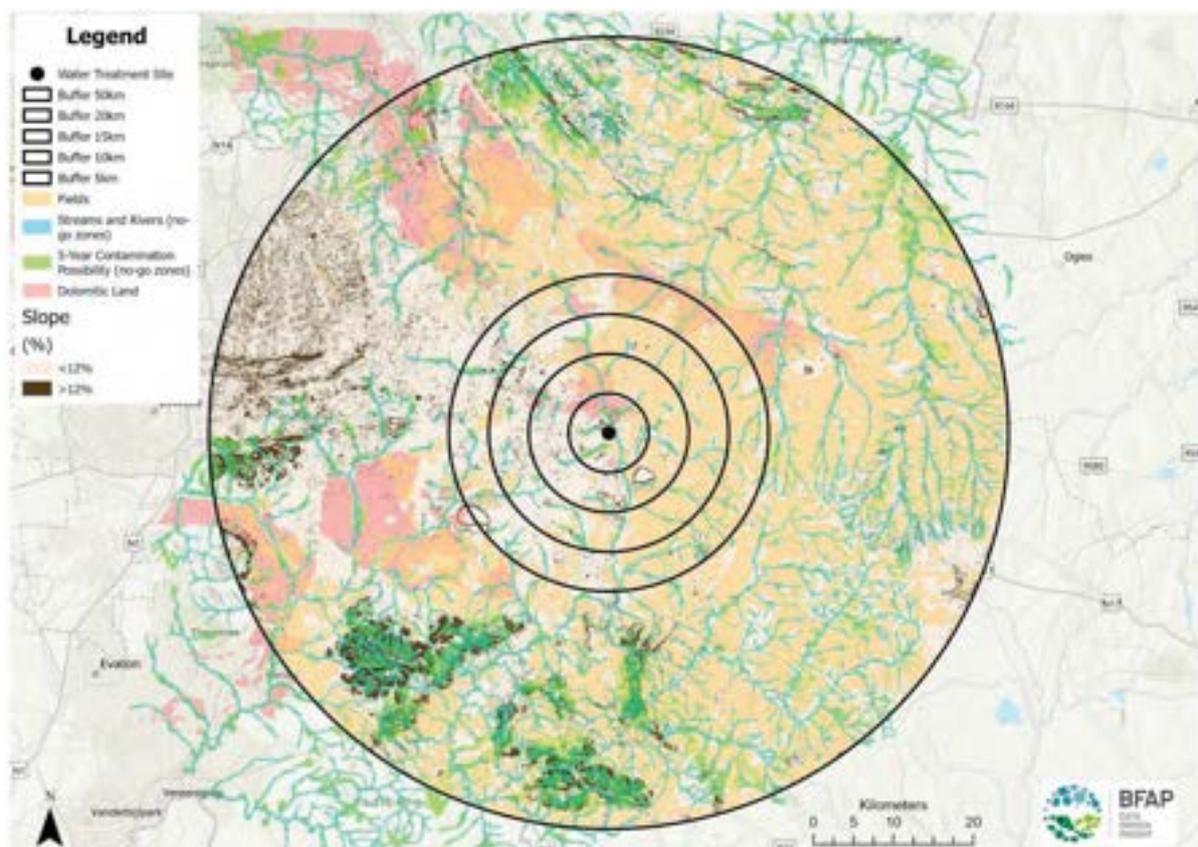


Figure 1.5 Hydrogeological no-go zones and slopes >12%

Table 1.4 Individual no-go zones

	5km	10km	15km	20km	50km
Dolomitic aquifers (ha)	390	1 944	2 007	5 343	34 219
Streams and rivers (ha)	212	1 926	5 505	10 160	89 518
Potential contamination (ha)	296	1 805	5 102	10 228	101 059

Since some water delivery system would be required from the Water Treatment Plant (WTP) to the existing cropland towards the East, a network analysis was conducted based on the road network, as it would be easier to lay pipelines along existing roads, given existing servitude zoning and the road reserves.

To indicate the pipeline's possible reach if laid along a road, a network analysis was conducted to provide a more accurate "buffer" than a simple radius analysis. Within ArcGIS's Network Analyst, the "Service Area" tool was used. A network service area is a region encompassing all accessible streets (that is, streets within a specified impedance). For instance, the 10 km service area for a point on a network includes all roads within 10 km of that point. A service area analysis was run using roads from an available data set, with 10 km and 20 km reaches. These respective areas are indicated in Figure 2.6 by the light purple area for the 10 km service area and the grey area for the 20 km service area.

Table 2.5 shows the areas of cultivated land within the buffer area, as well as the areas of land linked to a service area or road reserve within a 10 km radius and within a 20 km radius. There is ample land available in reasonably close proximity to the treatment site. Given the distribution of available land, the reach of a single irrigation pipeline would be minimal. The service network can be distributed in various directions, which may require an extensive pipeline for bulk water supply. A more detailed assessment of the area by engineers will be required to determine the optimal pipeline layout for an optimised bulk water supply to farmers.

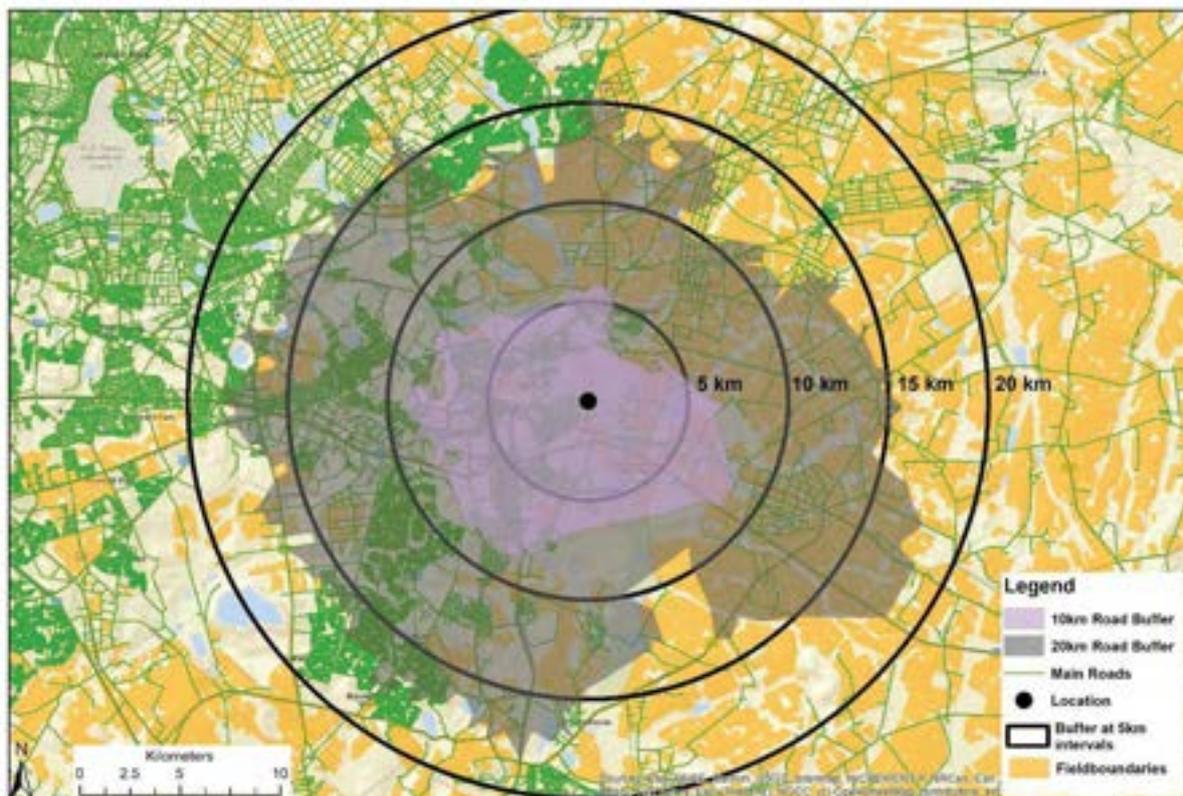


Figure 1.6 Map showing the road network as well as service areas within a 10 and 20 km radius, in relation to 5, 10, 15 and 20 km buffers with the field boundaries in the background.

Table 1.5 Area (ha) based on the field boundaries for 5, 10, 15 and 20 km buffer areas and a 10 and 20 km service area along the road network (i.e. road reserves to possibly be used for the bulk irrigation pipeline).

Field boundaries	5km	10km	15km	20km	10km Service Area / linked Road Reserve	20km Service Area / linked Road Reserve
Total cultivated fields	861	7 637	22 386	43 083	2 143	23 791
Total no-go zones	470	3 357	7 745	18 364		
% no-go zone fields of total cultivated fields	55%	44%	35%	43%		
Cultivated field classification: area excluding no-go zones						
Horticulture		2	2	6		2
Non-pivot irrigated Annual Crop Cultivation / Planted Pastures			15	29		
Old Fields			12	16		59
Pivot Irrigation	61	304	487	1 485	310	641
Rainfed Annual Crop Cultivation / Planted Pastures	840	5 286	15 564	23 947	1 772	21 128
Shade net			3	10		3
Small Holdings	30	466	1 730	2 503	31	1 542
Subsistence Farming			135	191	30	416

1.4.3 Socioeconomic profile

This section provides the socioeconomic context of the relevant local municipalities within a 50 km buffer zone of the site location (Figure 1.7). It is argued that produce from within a 15-20 km buffer zone from the site location could be transported or marketed to a broader area (hence, the 50 km zone). Table 1.6 presents demographic, income, poverty and employment indicators from the Census (2011) (StatsSA, 2011) as well as total livestock numbers owned by households, derived from the Community Survey 2016 (StatsSA, 2016). The local municipalities are listed in order of proximity and relative importance within the 50 km buffer zone.

Ekurhuleni is characterised by a very high population density (1 609 persons per square kilometre) and a high poverty incidence (27% of households in the municipality have an income below the upper-bound poverty line). The largest proportion of the population is between the ages of 15-34, and the calculated unemployment rate at the time was 21% (2016). The large unemployed young population is likely a good supply of labour. Due to high population density, households are recorded as owning more small animals (e.g., chickens) than large animals (e.g., cattle), which may create a market for small grains as feed. The profiling of Ekurhuleni further suggests that a large informal human market is close and therefore quite accessible from the study's area of interest.

The City of Johannesburg and the City of Tshwane have profiles similar to the Ekurhuleni local municipality, but fall within the “outskirts” of the 50 km buffer zone. These municipalities and communities are also potential markets for the produce, but higher transport costs will likely render them less profitable. The Victor Khanye local municipality in Mpumalanga is characterised by lower population density, lower poverty levels, and fewer livestock. On the other hand, the Govan Mbeki local municipality, which overlaps the 50 km buffer zone to the south-east, has a large population, and the community survey indicated that large livestock herds were maintained in this local municipality. This has potential for an informal animal feed market, but also poses risks of feed crop losses due to informal/communal grazing practices and theft.

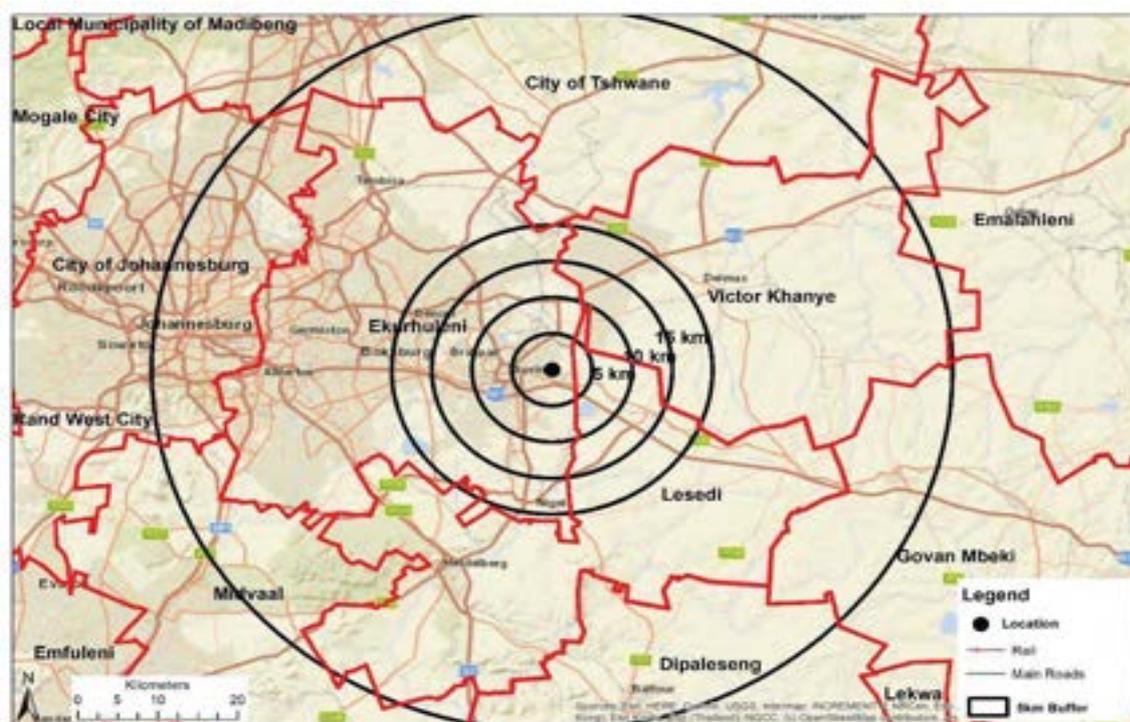


Figure 1.7 Local municipality delineations within the 50 km buffer zone around the WTP

Table 1.6 Socioeconomic indicators per local municipality

Indicator	Ekurhuleni	Lesedi	Midvaal	City of Johannesburg	City of Tshwane	Victor Khanye	Govan Mbeki	Dipaleseng
Province			Gauteng				Mpumalanga	
Total Population (2011) (Persons)	3 178 652	99 697	94 994	4 434 922	2 921 608	75 563	294 792	42 377
Age<15 (Persons)	817 225	27 379	23 327	1 086 363	717 573	22 567	84 000	12 659
Age 15-34 (Persons)	1 249 379	35 422	32 286	1 804 735	1 145 755	27 173	111 360	15 142
Age 35-44 (Persons)	475 212	14 009	14 751	672 401	432 733	9 916	39 075	5 228
Age 45-54 (Persons)	321 744	10 394	10 924	429 822	298 566	7 491	32 689	4 035
Age 55-64 (Persons)	187 523	7 083	7 820	257 769	184 592	4 967	16 602	2 735
Age >65 (Persons)	127 569	5 409	5 885	183 833	142 388	3 449	11 067	2 579
Population density (Persons/km ²)	1 609	67	55	2 696	464	48	100	16
Total number of Households	1 015 398	29 664	29 961	1 434 785	911 498	20 548	83 869	12 637
No-income households	181 291	4 071	4 315	238 058	135 861	3 016	13 700	1 384
Households earning less than the lower bound poverty line (LBPL)	220 318	5 270	5 171	282 058	161 581	3 910	17 033	2 169
Households earning less than the upper bound poverty line (UBPL)	273 478	6 995	6 781	344 421	200 669	4 904	21 623	3 044
LBPL incidence	22%	18%	17%	20%	18%	19%	20%	17%
LBPL density (Households/km ²)	111.54	3.55	3	171.47	25.66	2.49	5.76	0.83

Indicator	Ekurhuleni	Lesedi	Midvaal	City of Johannesburg	City of Tshwane	Victor Khanye	Govan Mbeki	Dipaleseng
UBPL incidence	27%	24%	23%	24%	22%	24%	26%	24%
UBPL density (households/km ²)	138.45	4.71	3.94	209.38	31.86	3.13	7.32	1.16
Dependents (Average per household)	2.89	3.06	2.85	2.81	2.94	3.25	3.1	3.12
Employed (Household Heads)	640 874	18 006	20 609	945 149	589 023	11 954	54 229	6 262
Unemployed (Household Heads)	146 151	3 376	2 709	171 448	100 801	2 179	10 490	1 871
Discouraged work seeker (Household Heads)	23 338	641	514	30 230	17 920	628	1 773	366
Not economically active (Household Heads)	204 174	7 602	6 128	286 403	202 781	5 715	17 289	4 122
Unemployment Rate	21%	18%	14%	18%	17%	19%	18%	26%
Cattle (Number of animals)	23 303	173 213	43 575	34 932	127 046	17 664	177 798	87 112
Pigs (Number of animals)	7 688	15 865	4 418	25 752	57 260	7 223	5 293	2 504
Sheep (Number of animals)	11 500	17 095	28 696	28 637	74 706	7 586	68 753	222 147
Goats (Number of animals)	11 391	12 314	5 232	76 306	66 654	2 913	8 437	2 724
Chickens (Number of animals)	131 459	150 018	115 313	198 179	949 283	48 864	226 790	26 024

1.5 CROP SELECTION

The objective of this section is to present the methodology by which a short list of potential irrigation crops was evaluated. The objective was to maximise water consumption through crop selection; however, it is important to note the disconnect between a consistent water supply and the seasonal nature of irrigation water consumption. The water treatment plant has the capacity to treat and release 85 megalitres of water per day, 365 days a year. The proposed water consumption for agricultural crop irrigation, however, shows marked seasonal demand patterns, depending on crop growth stage and external weather conditions (rainfall). Some water storage solution will be required to address the disconnect in the timing and quantity of water supply and demand, but this was beyond the scope of this research output. The crop rotation system selected can partially mitigate the seasonal water demand problem by combining summer and winter crops to ensure water use throughout most of the year.

To narrow the long list (>200) of potential crops for the farm-level model, a shorter list of the most suitable crops for the Highveld summer production area was selected (21) based on BFAP's industry knowledge and experience. This was followed by a pre-decision model together with a ranking methodology evaluating the shorter list of crops to propose a final crop selection for further investigation. The short list of crops considered for production under irrigation includes vegetable and cash crops for human consumption: potato, green maize, maize, wheat, sorghum, barley, sunflower, soybeans and canola; fodder crops for animal feed or biofuels applications: sweet sorghum (as silage), silage maize, Napier fodder, wattle trees; and annual and perennial pasture crops for animal feed: teff, oats, ryegrass, clover, lucerne, tropical grasses, Smuts finger/Rhodes and Eragrostis. Additionally, it was important to include non-edible industrial crops to address real and perceived concerns about the consumption safety of crops irrigated with mine waters.

The suitability of crops on the longer list was evaluated in stages. Figure 1.8 details how crops were eliminated from consideration in the case of "high risk" indications. The following indicators were considered in eliminating crops due to their perceived risk levels:

- **Risk factors:**
 - **Theft:** High | Medium | Low risk for extensive crop damage/loss due to theft.
 - **Fire:** High | Medium | Low risk for extensive crop damage due to fire incidents.
 - **Animal/Bird damage:** High | Medium | Low risk for extensive crop damage due to animal (e.g. cattle) or bird predation.
 - **Ease of production:** High | Medium | Low risk of crop damage due to incorrect production practices.

Following this process of elimination, the remaining crops were scored using the following indicators, each coded as a numerical value.

- **Socioeconomic Inclusiveness:**
 - **Labour multiplier** (Extensive = mainly machinery-driven field crops that imply low labour multipliers vs Intensive = some processes require manual processes implying a higher labour multiplier)
 - **Contribution to dietary diversity:** High (consumable directly from the field) | Medium (processing needed before fit for human consumption) | Low (not fit for human consumption)

- **Risk factors:**
 - **Theft:** High | Medium | Low risk for extensive crop damage/loss due to theft.
 - **Fire:** High | Medium | Low risk for extensive crop damage due to fire incidents.
 - **Animal/Bird damage:** High | Medium | Low risk for extensive crop damage due to animal (e.g. cattle) or bird predation.
 - **Ease of production:** High | Medium | Low risk of crop damage due to incorrect production practices.

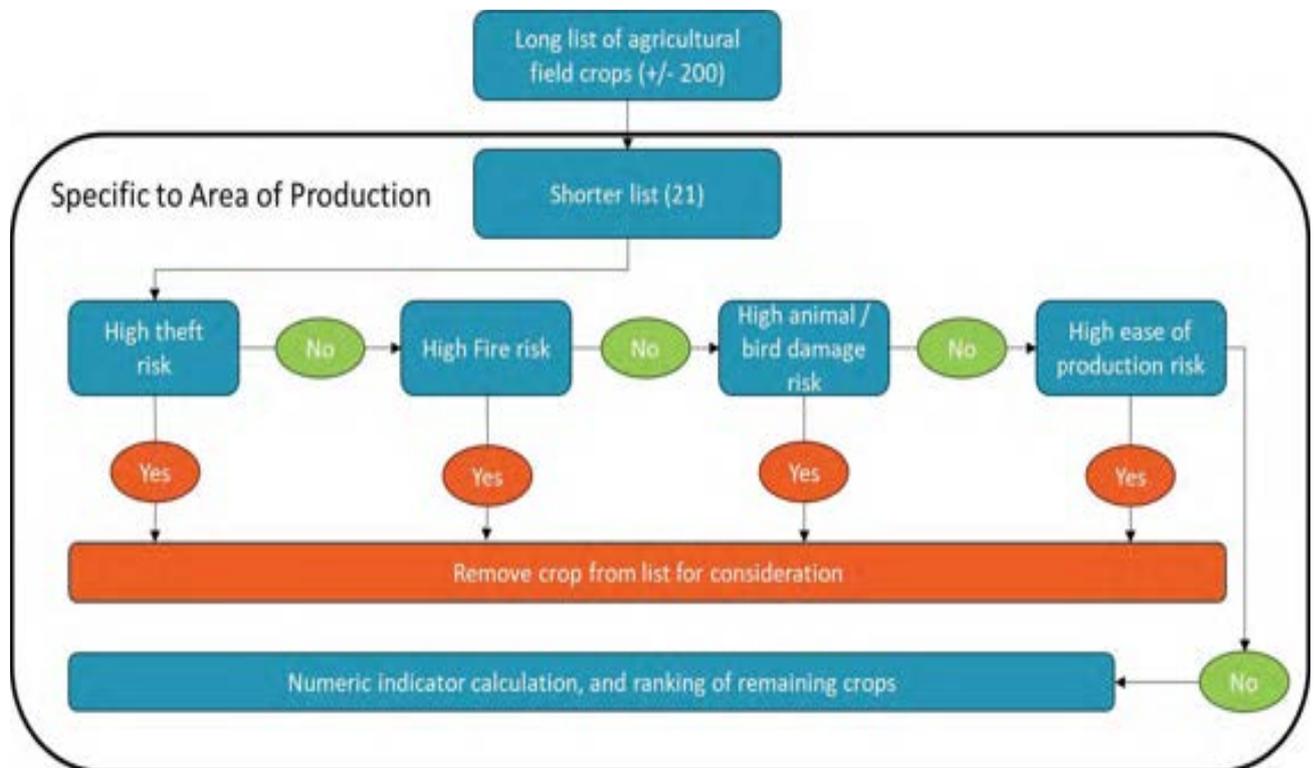


Figure 1.8 Crop elimination and ranking process

Scores of 1 to 3 were assigned to each of the above-mentioned indicators, where 3 indicates the best or highest positive score (e.g., low fire risk is assigned a score of 3, and a high contribution to dietary diversity is also assigned a score of 3). These scores were averaged to produce a combined score, and the crop ranking was assigned accordingly. Following several iterations of the process and consultation with local farmers, the following crops were selected for more detailed assessments: maize, oats, sweet sorghum, canola and soybean.

1.6 CONCLUSION

This chapter aimed to provide the background and context for the study, serving as a foundation for the assessments presented in the subsequent chapters. The next chapter will detail the work conducted to assess the productivity and consumption safety of crops irrigated with mine water from the Witwatersrand basins.

CHAPTER 2: IRRIGATION WITH GOLD MINE WATER FROM THE WITWATERSRAND BASINS

Over 20 years of research on commercial-scale irrigation in the Mpumalanga Coalfields of South Africa has demonstrated the feasibility of using circumneutral, calcium and sulphate-rich mine waters for irrigation. Irrigation with these has also been shown to remove quite large fractions of the salt applied to fields from the water due to the precipitation of gypsum within the (Annandale et al., 2006, Annandale et al., 2001, Jovanovic et al., 2002). The precipitation of gypsum reduces the salinity effects on crop yield and is not harmful to the crops.

Much like the waters that have been successfully used for irrigation in the Mpumalanga Coalfields, the mine water from the Witwatersrand basins is rich in calcium and sulphate and mostly circumneutral. Additionally, the long-term modelling and simulations conducted by Annandale, et al. (2023) predicted that irrigation with this mine water would be feasible. Although irrigation with Goldfields mine waters is expected to be successful, this has not yet been demonstrated, and concerns about crop productivity and the food safety of the produce remain. This component of the study aimed to address these concerns by establishing small-scale demonstration trials. The primary objectives were to assess the productivity and consumption safety of crops irrigated with mine waters.

At the inception of this study, several issues were noted that would make demonstrating irrigation with Goldfields mine waters at a field scale challenging. Firstly, there were uncertainties about whether the team would be granted access and/or permission to irrigate with mine water. Second was the lack of infrastructure to provide mine waters to commercially irrigated fields. Thirdly, a suitable collaborator(s) prepared to trial these waters without holding the research team liable for any real or perceived losses or impact had not been identified. Despite efforts to address these challenges, establishing a field demonstration trial proved infeasible, and a major hindrance was obtaining access to the mine waters.

To address the aim of demonstrating irrigation with untreated and partially treated mine-affected water in the Eastern Basin with limited access to mine waters, the research team opted to undertake glasshouse pot trials, which allowed for the assessment of all three basins' waters, in *lieu* of the small-scale demonstration trial with only Eastern Basin waters. Additionally, the project team sought to screen selected crops for their tolerance to irrigation with mining-influenced waters. Crop selection focused on economically important agronomic and pasture crops as described in Section 1.3. Special attention was given to identifying canola cultivars suitable for irrigation with saline mine waters from the Witwatersrand goldfields. This chapter presents the work completed to meet these aims.

2.1 CANOLA (BRASSICA NAPUS L.) CULTIVAR SELECTION FOR SALINE MINE WATER IRRIGATION

Canola (*Brassica napus* L.) is an important winter-growing oilseed crop, ranked globally second only to soybeans. In South Africa, most canola is produced in the Western Cape, where winter rainfall allows rain-fed cultivation. Due to current trends and optimistic projections, there is growing interest in growing canola in areas without winter rainfall, and there is potential for production in the Witwatersrand goldfields region. However, commercial irrigation from the Vaal River System, which supplies this region, was curtailed several years ago because it was not considered a priority use of water. Therefore, there is clear motivation to use other water sources, such as mining-influenced water, for irrigation.

Canola is reported to be relatively salt-tolerant, making it an ideal candidate for irrigation with mining-influenced water, which is often saline. Salinity tolerance has been reported to vary across growth stages, but the published threshold E_{Ce} for canola seed yield is 500 mS/m (Maas and Hoffman 1977). Although helpful in identifying canola as a salt-tolerant crop, this published figure is dated and may not apply to recently developed cultivars, particularly those available in South Africa. Additionally, the published threshold considers only Na⁺ and/or Cl⁻ dominated saline waters, which are expected to have more detrimental effects on crop growth than sulphate salinity.

Controlled environment experiments were conducted with synthetic saline solutions to assess how selected canola cultivars respond to sulphate-dominated salinity. The objective was to determine the salt tolerance thresholds of selected local canola cultivars and identify a cultivar most suited for irrigation with saline, sulphate-dominated mine waters. The experiments were conducted at the University of Pretoria Experimental Farm from April to September 2024. Pioneer Seeds provided four local canola cultivars for assessment: 45Y95 CL, 44Y94 CL, 43Y92 CL and PY520 TC. These cultivars represent the two main types of cultivars produced locally, early and medium maturing and exhibit attributes that are preferred, including herbicide resistance and tolerance to shattering, blackleg disease and drought. Table 2.1 shows the cultivar-specific attributes.

Table 2.1 Attributes of the cultivars used in this study.

Cultivar	Maturity	Herbicide resistance
44Y94CL	Early	Clearfield
45Y95CL	Medium	Clearfield
43Y92CL	Early	Clearfield
PY520TC	Medium	Clearfield and Triazine

2.1.1 Saline solution synthesis

Saline solutions were synthesised to simulate waters with sulphate salinities ranging from 200 mS/m to 600 mS/m, which is typical of mine waters from the Witwatersrand Goldfields. To synthesise the water, calcium sulphate (CaSO₄), magnesium sulphate (MgSO₄), and potassium sulphate (K₂SO₄) were used (insert Figure for reference). The use of Mg- and Ca-dominated sulphate waters reflects the composition of mine waters used for irrigation, as these waters typically contain higher concentrations of Ca²⁺, Mg²⁺, and SO₄²⁻. Calcium and magnesium sulphates naturally occur at mining sites and are also formed during the liming of acid mine water. Potassium sulphate (K₂SO₄) was used to raise the EC to the desired levels, as the combination of calcium sulphate and magnesium sulphate alone was insufficient to reach 600 mS/m due to gypsum precipitation.

The control had the lowest EC level (120 mS/m) and consisted of a nutrient solution mixture sourced from Hygrotech. The subsequent treatments, from the first to the last, included the nutrient solution along with the addition of CaSO₄, MgSO₄, and K₂SO₄. The nutrient solution was used to ensure nutrients were not a limiting factor in the trial. The concentrations of Ca, Mg, K, and SO₄²⁻ in the treatment solutions are presented in Table 2.2. The required salt concentrations to achieve the desired salinity levels were determined using the Aqion hydrochemistry software tool. The solutions were changed weekly to avoid nutrient deficiencies and extreme pH and EC fluctuations.

Table 2.2. EC (mS/m) and concentration (mg/L) of salts and elements in the saline solutions.

EC	CaSO ₄	MgSO ₄	K ₂ SO ₄	Ca	Mg	K	SO ₄ ²⁻
120				166	30	208	
200	560	20	20	331	34	217	352
300	800	370	370	402	105	374	910
400	1000	800	800	460	192	567	1540
500	1500	920	1300	608	216	791	2181

2.1.2 Germination assessment

According to Mass and Hoffman (1977), final germination percentage (GP) and germination rates are affected in saline environments. To assess these effects, daily germination was recorded to determine germination rate index (GRI), mean germination time (MGT), and final germination percentage. Germination experiments were conducted in a temperature-controlled growth chamber using the wet paper towel method. Fifty seeds were placed on a sheet of paper. Each sheet of paper towel was wetted with 100 ml of the treatment solutions described in Table 2.2, rolled up and covered with plastic to prevent evaporation. The samples were arranged vertically upright in a growth chamber set to 20°C as recommended by Haj Sghaier et al. (2022). Every 24 hours, the papers were opened, and a picture was taken for later counting of germinated seeds. This method was more rapid and helped prevent the paper towels from drying out.

The germination rate index (GRI), which is the weighted sum of the number of seeds germinated daily, was calculated using Equation 1 as proposed by Orchard (1977)

$$GRI = \sum \frac{G_t}{D_t} \quad \text{Equation 1}$$

Where G_t is the number of seeds germinated on day t , and D_t is the day number. This index indicates the proportion of seeds that germinated and the rate at which they germinated.

The mean germination time (MGT), which indicates the average number of days it takes for germination to take place, was determined using Equation 2 published by Ellis and Roberts (1981)

$$MGT = \frac{\sum n_i \times t_i}{\sum n_i} \quad \text{Equation 2}$$

Where n_i is the number of seeds germinated at time t_i , t_i is the time in days after planting, and $\sum n_i$ is the total number of seeds germinated.

The germination indices are presented in Table 2.3. All cultivars achieved a minimum germination percentage of 98%, and there were no significant differences in germination percentage among cultivars or across salinity treatments. This indicates that the assessed canola cultivar seeds can tolerate sulphate salinity up to 600 mS/m with no decline in seed viability. Generally, GRI decreased ($p < 0.05$), and MGT increased ($p < 0.05$) as the growth medium EC increased from 120 mS/m to 600 mS/m. This indicates that the sulphate salinity did affect the germination rate. Sulphate salinity effects on the germination were most pronounced in cultivar 43Y92CL, which experienced a significant decrease in GRI and MGT when salinity increased above 200 mS/m. Although sulphate salinity reduced the germination rate, the differences in MGT were no more than a day.

Boem et al. (1994) and Shrestha et al. (2025) observed a decrease in germination percentage when EC exceeded 600 mS/m, consistent with this trial, where germination percentage did not decrease significantly with increasing EC up to 600 mS/m. Salinity slowed germination, as evidenced by decreases in GRI and increases in MGT with rising EC. Ashraf and McNeilly (2004) similarly observed decreases in canola germination rate under saline conditions. They ascribed this result to osmotic stress limiting water absorption during imbibition. The relatively high GRI of 120-300 mS/m in cultivars 44Y94CL and 45Y95CL indicates that moderate salinity did not reduce germination rate in these cultivars.

Table 2.3 Mean germination percentage (%), mean germination rate index, and mean germination time

Cultivars	120	200	300	400	500	600
Germination percentage						
43Y92CL	100±0a	100±0a	100±0a	100±0a	98.67±1.33a	98±1.15a
44Y94CL	100±0a	100±0a	99.33±0.07a	100±0a	98.67±0.07a	98±1.15a
PY520TC	100±0a	100±0a	100±0a	100±0a	98.67±0.07a	100±0a
45Y95CL	100±0a	100±0a	100±0a	100±0a	100±0a	98±1.15a
CV%=0.9						
Germination rate index						
43Y92CL	24.50±0.096abc	24.11±0.056abcd	23.50±0.127def	21.86±0.165i	21.81±0.020i	20.86±0.235j
44Y94CL	24.83±0.167a	24.56±0.056abc	24.61±0.147ab	24.00±0.048bcde	22.89±0.121fgh	22.69±0.104gh
PY520TC	24.67±0.096ab	23.97±0.073bcde	24.00±0.048bcde	23.31±0.338efg	22.75±0.255fgh	22.34±0.116hi
45Y95CL	24.83±0.096a	24.17±0.048abcd	24.11±0.056abcd	24.03±0.028bcde	23.82±0.111cde	22.63±0.246gh
CV%= 1.0						
Mean germination time						
43Y92CL	2.06±0.011abc	2.11±0.007abcd	2.20±0.020defg	2.45±0.037ij	2.51±0.059jk	2.63±0.020k
44Y94CL	2.00±0.007a	2.05±0.007abc	2.02±0.007ab	2.13±0.007abcde	2.26±0.017efgh	2.43±0.044ij
PY520TC	2.04±0.012ab	2.14±0.012bcdef	2.14±0.012bcdef	2.23±0.052defgh	2.27±0.026fgh	2.33±0.024hi
45Y95CL	2.02±0.012ab	2.11±0.007abcd	2.11±0.007abcd	2.13±0.007abcde	2.18±0.023cdefg	2.28±0.024gh
CV%= 1.9						

Means with the same letter are not significantly different according to the protected LSD test at $p < 0.05$. Columns indicate mean \pm SE based on three replicates. Smaller SE values show higher consistency between replicates. CV% (SD÷mean) x 100, calculated separately for each cultivar x treatment combination. CV% reflects the relative variation of replicate measurements, with lower values indicating greater precision.

2.1.3 Vegetative biomass production and grain yield

The effect of sulphate salinity on canola productivity was assessed in a water culture. Seeds were first planted in seedling trays containing a 3:1 coir: silica sand mixture and kept moist with deionised water until germination. The trays were placed in a glasshouse and maintained at 22°C. After germination, seedlings received a nutrient solution at least once a week. After 21 days, vigorous seedlings were transplanted into 13-litre plastic containers filled with the treatment solutions described in Table 2.2. The seedlings were secured in the containers so that only the lower portion of the root system was in contact with the treatment solution. The containers were placed on a rotating table to ensure that all seedlings received equal exposure to light, minimising variations due to lighting conditions. Solutions were aerated with atmospheric air for 3 minutes every 30 minutes using a timer-activated air compressor. The amount of water used through evapotranspiration before the end of the week was replenished with deionised water regularly. Treatment solutions were replaced weekly to account for nutrient depletion and maintain a constant salinity.

At flower initiation (i.e., 50 days after planting), some of the plants were harvested to determine biomass production. In each treatment, at least one plant of each cultivar was harvested and oven-dried for 72 h at 65°C using brown paper bags, and the total dry mass was measured. The remaining plants were managed until they reached physiological maturity. At maturity, the pods were harvested and oven-dried. After drying, the pods were threshed to obtain the seeds, which were then cleaned and weighed. R-Studio was used to analyse data. Electrical conductivity (EC) thresholds and slopes were estimated using the data and the Maas and Hoffman (1977) methodology.

Vegetative biomass and grain yield are presented in Table 2.4. There was a general decrease in crop productivity as salinity increased. The control had the highest biomass across all cultivars, whereas 600 mS/m had the lowest. Cultivar 44Y94CL biomass remained statistically insignificant ($p < 0.05$) across all salinity levels, whereas the other cultivars began to show a decline in biomass at a salinity of 500mS/m. There was no consistent decrease in yields with increasing growth medium EC, and there were no significant differences in seed yield across all treatments. Additionally, the coefficient of variation (CV) was extremely high (56%), indicating that observed differences were not due to treatment effects.

The productivity of cultivar 44Y94CL across all salinity levels indicates its relative tolerance to salinity. This contrasts with cultivars PY520TC and 45Y95CL, which showed notable decreases in vegetative biomass as the growth medium EC increased above 400mS/m. Overall, this study's findings are consistent with those of other studies, indicating that canola vegetative growth is more susceptible to salt than seed production (Bahizire, 2007). Due to inconsistencies in the data, the assessment of sulphate salinity on seed yield was inconclusive. However, canola and other moderately salt-tolerant oilseeds have been found to decrease biomass without a yield penalty under moderate salinity (Steppuhn & Wall, 1999). According to these results, breeding for genotypes such as Cultivar 44Y94CL may increase salt resistance without lowering productivity.

The salinity trials provided valuable insights into how selected canola cultivars respond to sulphate-dominated salinity. The yield results were inconclusive; however, biomass results indicate that the vegetative stage is sensitive to salinity, and that salinity tolerance was higher in early-maturing cultivars than in medium-maturing ones. Nonetheless, irrigation with the Witwatersrand Goldfields mine waters is not expected to result in salinity-induced yield reduction in canola. The 44Y94CL cultivar was identified as having the greatest potential for successful irrigation with the saline mine waters and was therefore selected for further assessment.

Table 2.4 Mean vegetative yield (g/plant) 50 days after planting, and seed yield (g/plant) after harvesting.

Hybrids	120 mS/m	200 mS/m	300 mS/m	400 mS/m	500 mS/m	600 mS/m
Vegetative yield						
43Y92CL	3.3±0.7abcd	3.2±1.1abcd	2.2±0.5abcde	1.4±0.1bcde	1.2±0.6de	1.3±0.5cde
44Y94CL	3.7±0.4abc	3.4±0.4abcd	2.7±0.4abcde	2.2±0.1abcde	2.3±0.1abcde	2.1±0.3abcde
PY520TC	3.7±0.4ab	2.2±0.5abcde	2.3±0.1abcde	1.9±0.5abcde	0.8±0.2e	0.8±0.1e
45Y95CL	3.9±0.1a	3.6±0.5abc	2.9±0.6abcde	2.0±0.2abcde	1.5±0.2bcde	1.4±0.2bcde
CV% = 32						
Seed yield						
43Y92CL	9.6±0.7a	11.8±2.7a	5.4±0.7a	7.7±2.1a	10.3±1.5a	8.1±1.0a
44Y94CL	8.0±5.3a	7.4±3.6a	5.8±0.7a	3.6±1.2a	5.9±2.6a	9.3±2.7a
PY520TC	4.7±1.7a	6.0±0.5a	3.7±1.5a	9.9±3.2a	3.8±0.4a	3.5±1.1a
45Y95CL	3.8±1.1a	6.0±2.3a	3.8±2.4a	8.6±2.2a	5.8±1.1a	4.2±1.3a
CV% = 56						

Means with different letters indicate a significant difference at $p < 0,05$ using the LSD test. Columns indicate mean \pm SE based on three replicates. Smaller SE values show higher consistency between replicates. CV% $(SD \div \text{mean}) \times 100$, calculated separately for each hybrid x treatment combination. CV% reflects the relative variation of replicate measurements, with lower values indicating greater precision.

2.2 CROP AND SOIL RESPONSES TO SELECTED CONSTITUENTS OF CONCERN IN MINING-INFLUENCED WATER FROM THE WITWATERSRAND GOLDFIELDS

A common characteristic of mining-influenced water is the acidity and the high concentration of dissolved solutes and trace elements. The quality of mining-influenced water is strongly influenced by the chemical composition of the geological strata in the area, as demonstrated by the Witwatersrand Basin. The Western and Central Basins of the Witwatersrand produce typical AMD, while the Eastern Basin produces near-neutral water with lower sulphate and trace element concentrations. The seemingly better water quality in the Eastern Basin is primarily attributed to the dolomitic layers that cover it and to the ingress of dolomitic water from the dolomitic aquifer in its vicinity. The dolomite increases the pH of the mine water and, in the process, reduces metal and sulphate concentrations (DWA, 2013).

In contrast, there is no ingress of dolomitic water in the Central and Western Basins, which are buried beneath the Black Reef Formation and overlain by a thin layer of dolomite. In the Western Basin, the dolomitic layer has decomposed into an iron-manganese oxide mixture with little or no acid-neutralising capacity. In the Central Basin, the Black Reef Formation is separated from the dolomitic layer by volcanic rock, which precludes the interaction between the dolomite and the basin's mine water. This results in a slightly more acidic water with a higher concentration of sulphates and trace elements. Although there are variations in mine water quality across the different basins, certain constituents are commonly found in all these waters. These include major cations and anions, Ca, Mg, Na, SO₄ and Cl, which are the main contributors to the salinity of the waters, as well as Al, Fe and Mn, which can be phytotoxic and zootoxic when available at high concentrations.

As a first step toward demonstrating the suitability of the goldfields mine waters for irrigation, glasshouse pot trials were conducted at the University of Pretoria to assess crop and soil responses to the main constituents of concern in the goldfields mine waters. This entailed irrigating selected crops with synthetic mine waters containing the major constituents, and the rationale was that success with these waters would provide a good indication of the suitability for irrigation.

2.2.1 Mine water synthesis

The water quality data the project team received when the trials were initiated was not comprehensive. In the Eastern and Central Basins, water quality data included only pH, EC, Ca, Mg, Na, SO₄, Cl, Al, Fe, and Mn; these were identified as the main constituents of concern. Mine waters were therefore designed to include only these elements. The rationale was that being successful with mine waters containing the major constituents of concern would be a good indication that the waters are suitable for irrigation. Mine waters were synthesised based on the target water qualities presented in Table 2.5. These target water qualities were derived from the 95th percentile of constituent concentrations and the 5th percentile for pH, to provide a "worst-case" assessment of the suitability of these waters for irrigation.

Since the Goldfields mine waters are dominated by sulphates, mostly sulphate (SO₄²⁻) salts were used to synthesise the waters. The amount of salt required to obtain the target concentration of each element or ion was calculated using Equation 3 below, where [Required Salt] is the amount of salt that needs to be added to a litre of solution (mg/L), [Element] is the target concentration of the element or ion (mg/L), M_{salt} is the molar mass of the required salt (mg/mmol), M_{element} is the molar mass of the desired element (mg/mol), n_{salt} is the moles of salt (mmol) and n_{element} is the number of moles of the desired element or ion present in the specified moles of salt (mmol).

$$[Required\ salt] = [Element] \times \frac{M_{salt}}{M_{element}} \times \frac{n_{salt}}{n_{element}} \quad \text{Equation 3}$$

The mine waters were synthesised by adding calculated amounts of FeSO₄·7H₂O, MnSO₄·7H₂O, MgSO₄·7H₂O, Na₂SO₄, Al₂(SO₄)₃·18H₂O and CaCl₂·2H₂O to a gypsum solution (CaSO₄·2H₂O), as sources of the major elements. The waters from the Witwatersrand Goldfields contain some alkalinity; therefore, CaCO₃ was added to adjust the alkalinity as required.

Table 2.5 Target water qualities for synthetic mine waters: element concentrations in mg/L, EC in mS/m, and pH unitless.

Constituent	EB AMD	EB HDS	CB AMD	CB HDS	WB AMD	WB HDS
pH	6.14	7.23	5.57	7.28	6.34	8.68
EC	277	265	464	406	373	370
Ca	353	366	487	741	653	838
Mg	118	125	176	155	203	125
Na	203	204	183	181	175	186
SO ₄ ²⁻	1215	1252	3457	2702	2290	2419
Cl	115	120	83	82	83	81
Al	0.26	0.10	0.15	0.15	2.4	0.14
Fe	83	0.67	514	0.24	111	1.1
Mn	5.5	3.5	26	4.2	79	1.2

2.2.2 Trial design and management

The crop trials were conducted at the University of Pretoria Innovation Africa Farm. In this trial, sorghum and soybean were assessed. The crops were grown in pots filled with red sandy loam soil collected from the University of Pretoria Innovation Africa Farm. The soil was analysed for pH (in KCl), saturated paste electrical conductivity (EC_e), and plant-available concentrations of the major constituents of concern in the mine waters (using a Melich III extraction) to determine the initial soil conditions. The results are presented in Table 2.6. The trial consisted of seven treatments: the six synthetic mine waters discussed in the previous section and a control treatment of deionised water. Each treatment was replicated three times, and crops were grown to maturity.

Table 2.6 Chemical properties of the soil used in the synthetic mine water irrigation pot trial. Concentrations are in mg/kg, ECe in mS/m and pH without units

Constituent	Concentration/Level
pH (KCl)	4.07
EC _e	14
P	22
K	71
Ca	238
Mg	58
S	12.9
Na	14
Al	652
Fe	49
Mn	48

Irrigation was applied when the soil water was depleted by 40%. The irrigation amount was determined by weighing the pots and calculating the amount of water required to reach field capacity. Field capacity was determined at the beginning of the trial and recalibrated 8 weeks after planting to account for crop growth. The initial field capacity was determined by irrigating the soil to saturation and covering it with plastic. The pots were left to drain for 72 hours and weighed to determine field capacity. A similar approach was used when recalibrating, except that the pots were not covered with plastic after irrigation to saturation and were weighed after 24 hours rather than 72 hours due to the crops.

Lime was applied to adjust soil pH and neutralise acidity introduced by the synthetic mine water treatments. The liming application rate for soil acidity was determined experimentally according to the method described by Kissel et al. (2007). Analytical grade CaCO₃ was used for liming. The liming rate in mg CaCO₃ per pot, for each mine water treatment, was calculated based on the acidity of the water as indicated in Equation 4 below:

$$\text{Liming Rate} = V_{\text{applied}} \times \text{Acidity} \quad \text{Equation 4}$$

where V_{applied} is the total volume of water that will be applied throughout the season in litres per pot (L/pot), calculated based on crop water requirements, and acidity is the acidity of the mine water reported as mg CaCO₃/L. Fertiliser was applied to obtain optimum soil nutrient levels and meet plant requirements. The fertiliser application rate was calculated according to the guidelines provided in the Fertiliser Handbook (FSSA, 2000).

2.2.3 Soil pH and saturated paste electrical conductivity (ECe)

At the end of the trial, composite soil samples for each crop were analysed to determine pH (in KCl) and saturated paste electrical conductivity (ECe).

There were differences between the initial and final pH of the soils (Figure 2.1). The final pH of all soils was higher than the initial pH, which can be attributed to the lime applied to raise it. There were also differences in pH between the water treatments. The pH of soils irrigated with mine waters, especially the untreated mine waters, was higher than that of the control soils. This indicates that the untreated waters did not acidify the soils, suggesting that the additional lime applied was sufficient to neutralise the acidity in these waters.

There was an increase in EC_e in all the treatments, including the control and the mine water, and the EC_e of the soils irrigated with the mine waters was higher than that of the controls (Figure 2.2). However, the EC was generally below 200 mS/m, which is suitable for the growth of most crops, including moderately sensitive crops.

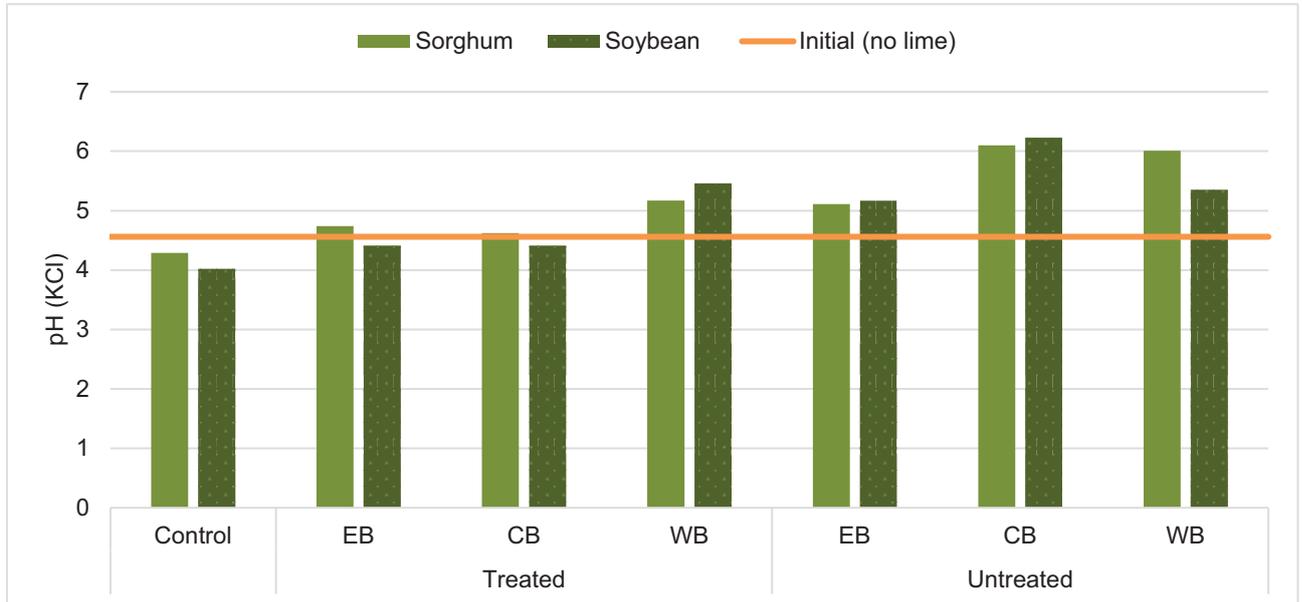


Figure 2.1. Soil pH before and after irrigation with the synthetic mine waters.

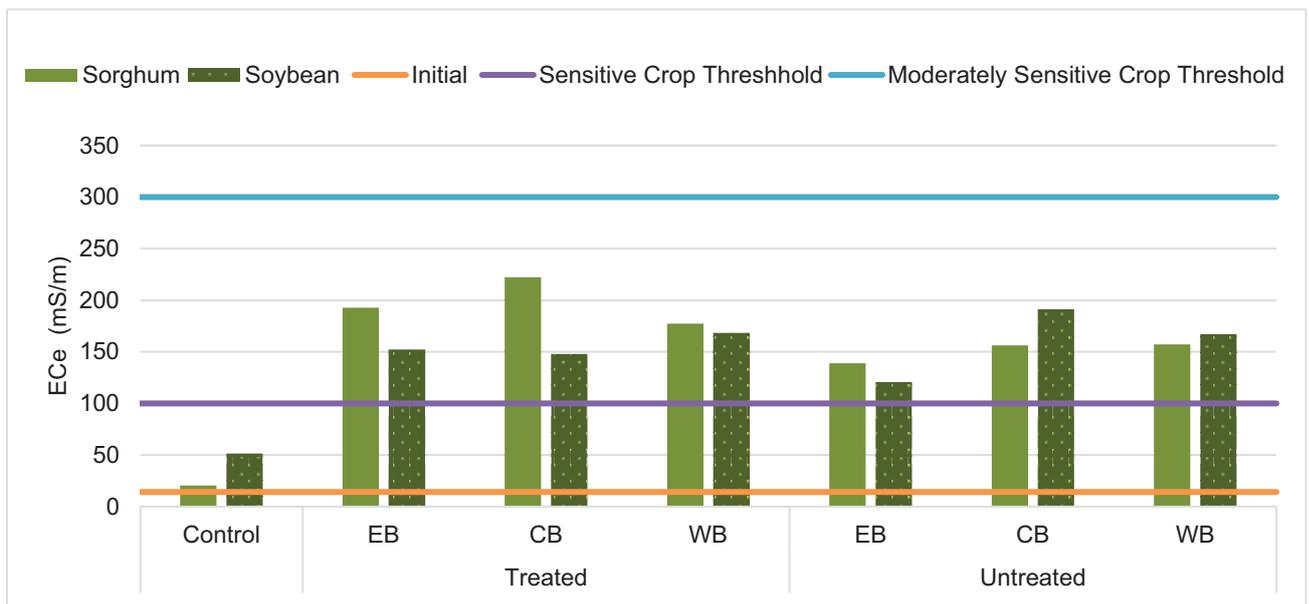


Figure 2.2 Soil EC_e before and after irrigation with the synthetic mine waters.

2.2.4 Crop productivity

When crops reached physiological maturity, they were harvested, and the plant material was oven-dried. After drying, dry mass and yield measurements were performed. Table 2.7 shows the aboveground dry mass of the assessed crops. There were no significant differences in dry mass between the mine water treatments and the control treatment in all crops except soybean. Soybean irrigated with untreated mine water from the Western Basin produced more dry matter than the control; however, there were no significant differences between the mine water treatments.

There were no significant differences in grain yield between the mine water treatments and the control treatment in sorghum (Figure 2.3a). However, sorghum irrigated with EB mine water generally had a lower yield than that irrigated with the other mine water. The CB mine water treatments generally produced higher yields than the different treatments, which is counterintuitive given that the CB treatments were more saline. Soybean irrigated with untreated mine water from the Western Basin had a higher yield than the control (Figure 2.3b). However, there were no significant differences in yield between the mine water treatments. Overall, the results indicate that the mine water treatments did not cause any significant yield reductions in any of the crops.

Table 2.7 Average aboveground dry mass (kg/pot) of sorghum and soybean irrigated with synthetic mine waters. Means with similar letters are not significantly different.

Treatment	Sorghum	Soybean
Control	0.051 b	0.147 ab
EB Treated	0.064 ab	0.144 ab
CB Treated	0.061 ab	0.161 a
WB Treated	0.067 ab	0.153 a
EB Untreated	0.066 ab	0.122 b
CB Untreated	0.064 ab	0.159 a
WB Untreated	0.071 a	0.146 ab

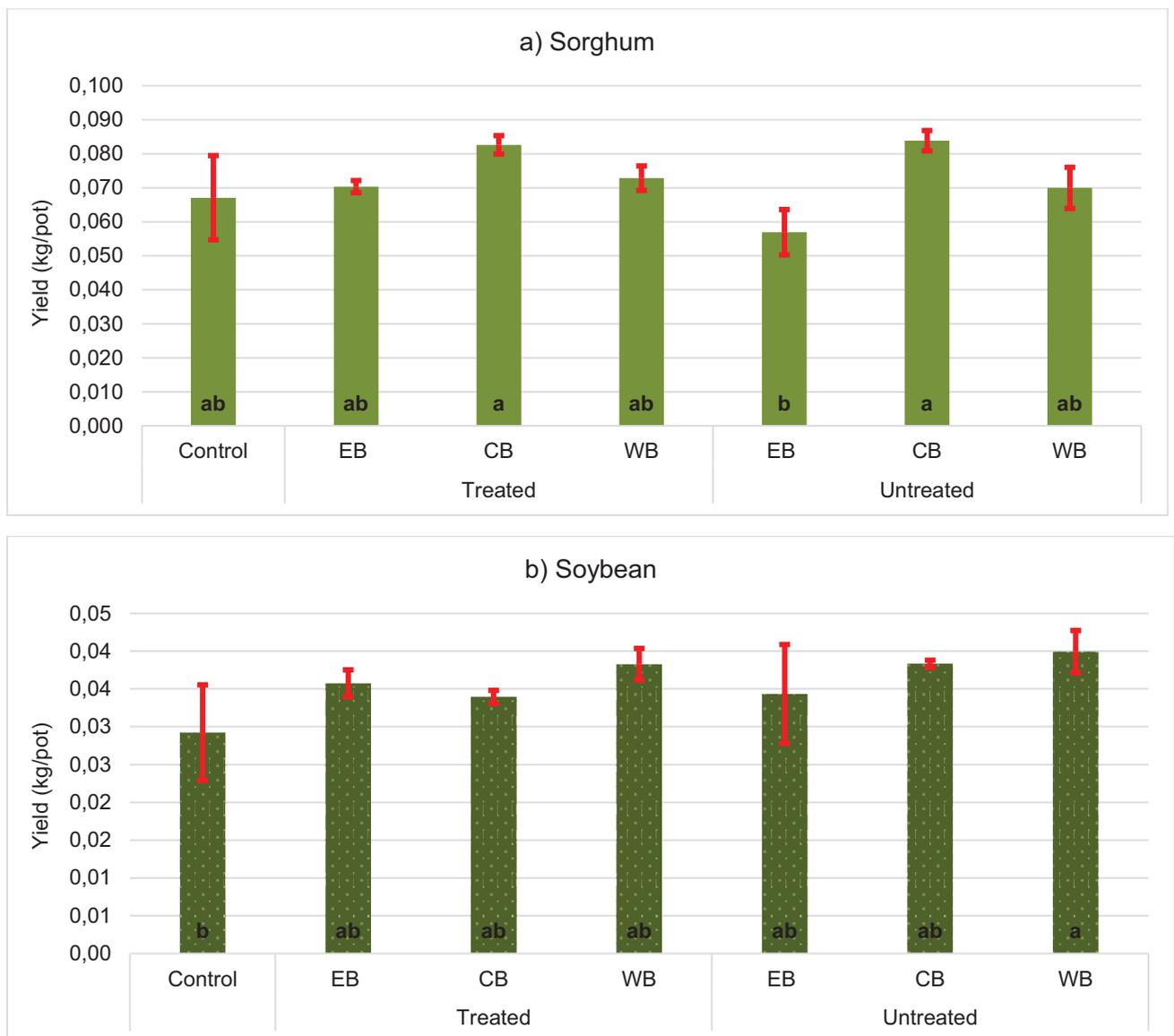


Figure 2.3 Average yield of a) sorghum and b) soybean irrigated with synthetic mine waters.

2.2.5 Concentration of constituents of concern in crops

At harvest, composite samples of plant material were collected and analysed to assess the accumulation of constituents of concern (Al, Fe, Mn, and Na). Fe and Mn are essential elements for crop growth, and Al and Na are harmless to crops when present at low concentrations. However, these elements can cause phytotoxicity if they accumulate to high concentrations in crops. The foliar concentrations of Al, Fe, Mn and Na are presented in Table 2.8. Sorghum irrigated with the mine waters accumulated higher levels of Na and Mn than the control. There was also a higher accumulation of Fe in sorghum irrigated with the EB water and the treated WB mine water.

Table 2.8 Foliar concentration (mg/kg) of Al, Fe, Mn and Na in crops irrigated with synthetic mine waters. Values in red indicate concentrations higher than the control.

Treatment	Na	Al	Fe	Mn
Sorghum				
Control	66	170	345	535
EB Treated	120	163	394	550
CB Treated	119	191	302	654
WB Treated	128	164	381	563
EB Untreated	123	170	489	624
CB Untreated	92	146	305	622
WB Untreated	83	142	313	608
Soybean				
Control	72	497	465	1014
EB Treated	107	526	561	983
CB Treated	128	535	463	899
WB Treated	97	522	413	953
EB Untreated	97	455	478	913
CB Untreated	92	542	810	1542
WB Untreated	89	494	719	1259

Although irrigation with the mine waters did not significantly reduce crop yields, sorghum yields were notably lower when irrigated with untreated EB mine water than with the other waters. This was unexpected, as EB waters are generally of higher quality for irrigation than other waters, with lower salinity and lower concentrations. The absence of significant differences in biomass and yield between crops irrigated with simulated mine water treatments and the control indicated that the assessed constituents did not cause significant yield reductions.

Except for Fe accumulation in sorghum, there was no clear relationship between the uptake of selected mine water constituents and crop productivity. Crops irrigated with untreated CB mine waters were expected to perform the poorest, as these waters have the highest salinity and the highest concentrations of Fe and Mn, which can be phytotoxic. However, this was not the case; instead, the most notable yield reductions were observed in crops irrigated with treated water, which were initially expected to be among the best-performing treatments.

Irrigation with synthetic mine waters provided valuable insights into crop responses to the major constituents of mine water from the Witwatersrand basins. The absence of significant differences in crop productivity between synthetic mine waters and control treatments indicated that these waters can be used for irrigation with minimal or no yield penalties. The study also highlighted differences in crop uptake of elements and crop-specific sensitivities to certain elements. Overall, the results of this study indicated that irrigation with the Witwatersrand goldmine waters is possible. However, assessments using real mine waters were required to account for their complexity.

2.3 CROP AND SOIL RESPONSES TO IRRIGATION WITH REAL MINE WATERS FROM THE WITWATERSRAND GOLDFIELDS

Synthetic solutions provide a convenient, accessible means of assessing chemical reactions in a consistent, reproducible manner, and the trials conducted with synthetic mine waters allowed assessment of crop responses to the major constituents of the Witwatersrand. However, the simulated waters did not account for the complexities of real mine waters. A notable shortcoming of the trial was that certain trace elements found in the real mine waters were not included in the synthetic mine water mixtures due to limitations in accessing suitable sources of the elements.

The promising results obtained from the experiments conducted with synthetic mine waters, as presented in Section 2.2, facilitated access to real mine waters. However, regulators limited the use of these real mine waters to glasshouse trials. Therefore, glasshouse pot trials were conducted to investigate crop and soil responses to irrigation with real untreated and HDS-treated mining-influenced water from the Witwatersrand basins and to assess the food and feed safety of the produce.

Winter and summer crops were established in July and December 2024, respectively, at the University of Pretoria Innovation Africa Experimental Farm. Oats and canola were planted in the winter trial, and maize, soybean and sweet sorghum were planted in the summer trial. Crops were grown in 6 L pots filled with 7.5 kg of red sandy loam soil sourced from the experimental farm fields. Maize and soybean were planted in the same soil used during the winter trial to simulate two seasons of irrigation.

Soils irrigated with untreated mine water were limed with reagent-grade CaCO_3 to neutralise the water's acidity. Lime application rates were determined based on water acidity and seasonal crop water requirements. The trial consisted of six treatments of treated and untreated mine water collected from the three Witwatersrand treatment plants for irrigation. The mine waters were analysed three times during the trial at an accredited laboratory, and the average quality is presented in Table 2.9. Analysis methods are listed in the laboratory accreditation certificate (Waterlab 2024). Deionised water was used as a control treatment. Each treatment was replicated four times.

Table 2.9. Average qualities of mine water collected from the EB (Eastern Basin), CB (Central Basin), and WB (Western Basin). Concentrations are in mg/L; acidity and alkalinity in mg/L CaCO₃ eq.; EC in mS/m; and pH without units.

Parameter	EB untreated	CB untreated	WB untreated	EB HDS treated	CB HDS treated	WB HDS treated
pH	6.60	5.80	6.33	7.53	8.20	9.33
EC	258	384	342	249	375	331
TDS	2141	4185	3323	2107	4027	3642
Acidity	105	427	100	7	5	5
Alkalinity	337	31	43	289	21	44
Ca	334	538	616	328	785	697
Mg	100	162	94	97	138	71
Na	171	157	165	161	155	159
SO ₄	941	2317	1882	950	2280	1864
Cl	86	57	47	84	56	47
F	533	233	400	433	200	333
Al	0.059	0.140	0.100	0.133	0.100	0.129
As	0.203	0.239	0.300	0.003	0.056	0.011
B	0.265	0.451	0.075	0.249	0.169	0.074
Cd	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cr	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025
Co	<0.025	0.159	0.181	<0.025	<0.025	0.174
Cu	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Fe	79	276	46	1	1	1
Pb	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Mn	257	19	17	2	1	0
Hg	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Mo	0.013	0.009	0.009	0.009	0.009	0.009
Ni	0.043	0.308	0.032	0.031	0.025	0.025
U	0.056	0.004	0.105	0.047	<0.001	0.015
Zn	0.028	0.063	0.029	0.026	0.025	0.032

The trials were managed in the same way as described in Section 2.2.2 . After germination, the crops were irrigated to field capacity with a nutrient solution instead of the treatment irrigation water once a week. Therefore, crops with higher water requirements received a greater amount of the nutrient solution. Maize, soybean, canola and oats were harvested at maturity, and aboveground biomass and grain yield were determined. Sweet sorghum was harvested after full flowering, and aboveground biomass was determined.

Composite samples of the aboveground plant material and/or the grain of maize, oats, and sweet sorghum were analysed to determine the concentration of selected elements. Composite soil samples of each water treatment were analysed to determine the effect of the mine water treatments on selected chemical properties, including pH (KCl), saturated paste electrical conductivity (ECe) and total heavy metal concentrations.

Statistical analyses were performed in SAS® Studio. Analysis of variance (ANOVA) was used to assess the effects of the mine water on aboveground biomass production and seed yield. Mean comparisons were performed using Tukey's Studentized Range (HSD) Test.

2.3.1 Soil pH and saturated paste electrical conductivity (ECe)

The analysis results show that there were differences between the initial and final pH of the soils (Figure 2.4). The final pH of all soils ranged from 5.9 to 7.7, which was higher than the initial pH before liming. Even after two seasons of irrigation, the pH of the soils irrigated with mine waters remained above the initial pH. The lowest pH (6.1) was observed after the second season of irrigation in soils irrigated with untreated WB mine water.

Irrigation with the mine water increased the saturated paste electrical conductivity (ECe) of the soils substantially from the initial condition, and there was a substantial increase from the first season to the second season (Figure 2.5). The most notable increase was observed in soils irrigated with the untreated WB mine water, with EC increasing from 173 mS/m in the first season to 379 mS/m. Despite this increase, maize irrigated with the WB water was more productive than the other treatments, as shown in Figure 2.7, indicating that there were no negative effects of salinity on crop performance. There was also a substantial increase in the ECe of the control soil from 26 mS/m in the first season to 92 mS/m in the second season.

The soil analyses indicated that liming substantially reduced soil acidification, particularly in soils irrigated with untreated mine water. The increase in ECe from the first to the second season indicates an accumulation of salts in the soil profile. Additionally, a substantial increase in EC was also observed in the control treatments, which was due to the nutrient solution. The accumulation of salts in the profile can be addressed by applying an appropriate leaching fraction.

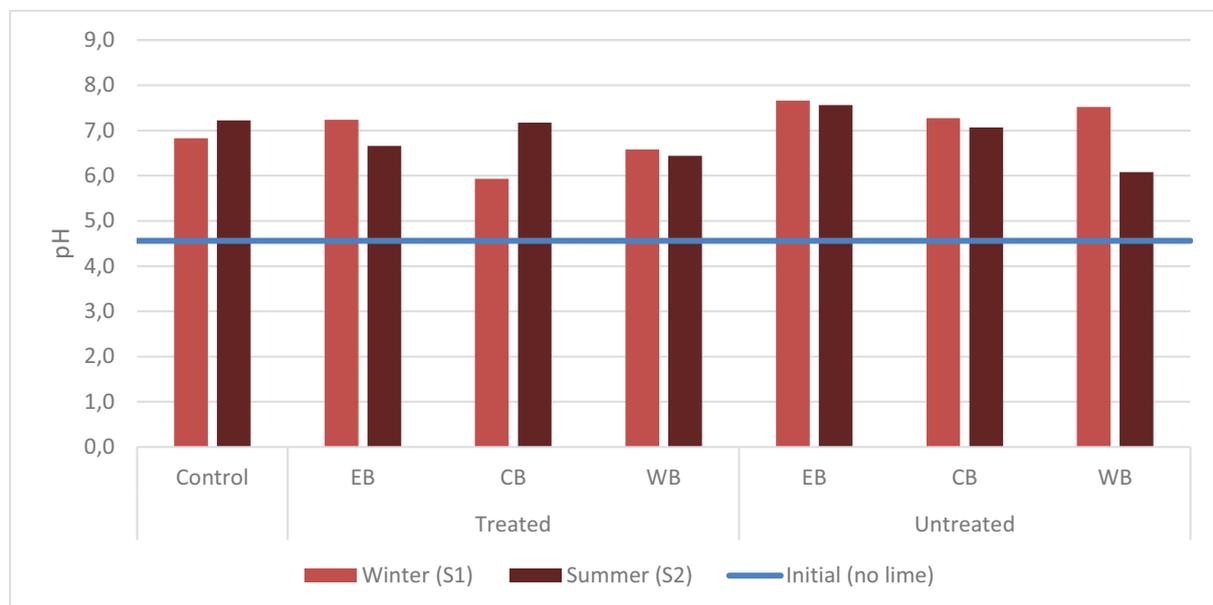


Figure 2.4 Soil pH before liming and after irrigation with real mine waters.

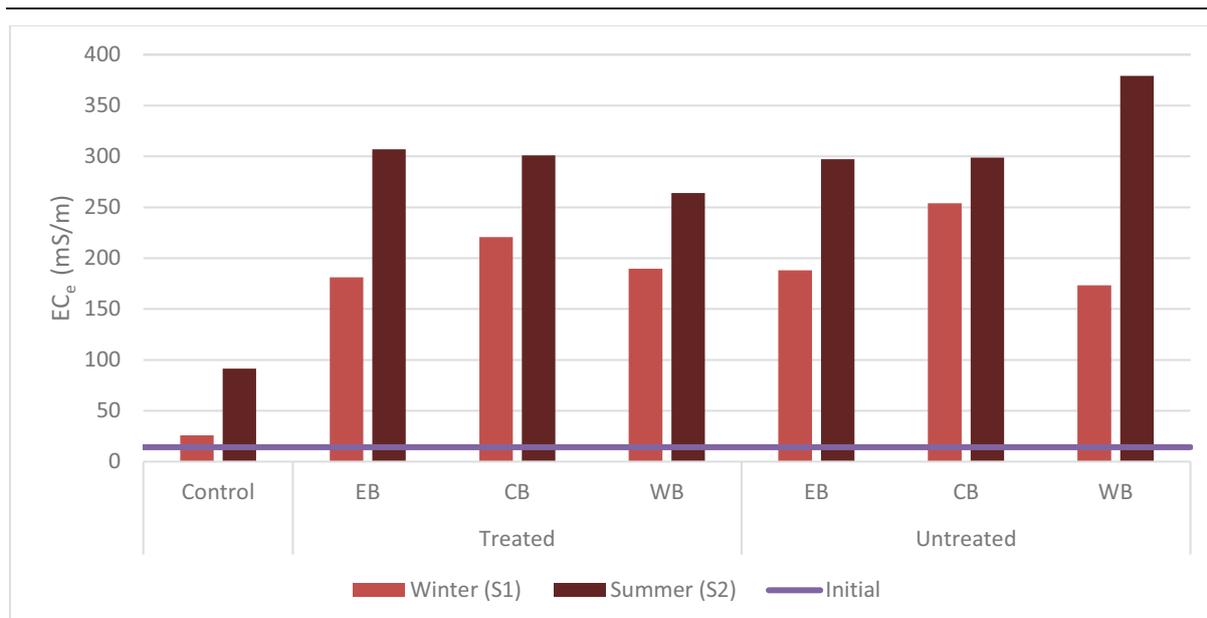


Figure 2.5 Soil ECe before and after irrigation with real mine waters.

2.3.2 Crop productivity and yield

2.3.2.1 Winter crops

The mean aboveground vegetative biomass is presented in Table 2.10 and the yield is presented in Figure 2.6. Canola irrigated with the mining-influenced waters produced 0.04 to 0.56 kilograms of biomass per pot (kg/pot) on average, while the control produced 0.05 kg/pot. Oats irrigated with the mining-influenced waters produced 0.10 kg to 0.14 kg/ pot, while the control treatment yielded 0.11 kg/pot. Irrigation with the mine water generally had no significant effect on vegetative biomass production of the winter crops.

Oats irrigated with the mining-influenced waters yielded 0.034 to 0.073 kg grain/pot, while the control treatment yielded 0.035 kg/pot. Canola irrigated with the mining-influenced waters yielded 0.004 to 0.021 kg seed/pot, while the control yielded 0.007 kg/pot. Irrigation with the mine water generally had no significant effect on the winter crop. However, the yield of winter crops irrigated with untreated CB mine water was notably lower. The reduction in canola biomass production and yield under irrigation with untreated CB mine water was due to soil crusting after planting, which inhibited germination.

To mitigate data loss, pots that did not germinate were replanted, and the surface was kept moist to prevent crusting. Consequently, the development of the replanted crops was delayed. However, an important observation was made regarding the effect of the CB waters on the soil physical properties. This learning has implications for irrigation management if the large-scale rollout of irrigation with the untreated CB mine waters is adopted. High sodium levels, low organic matter, high magnesium concentrations relative to calcium, and high iron and aluminium oxide content can cause crusting. In this case, the crusting was likely due to the formation of iron oxides when the iron from the water reacted with the liming material, which can aggregate and cement soil particles (Meimaroglou and Mouzakis, 2025). The untreated CB water had the highest iron concentration, which likely made these effects more pronounced in soils irrigated with it.

Table 2.10. Mean aboveground vegetative dry mass of oats and canola irrigated with mine water. Means with the same letter are not significantly different (p-value = 0.0198). Units are kg/pot.

Treatment	Canola	Oats
Control	0.05±0.012 a	0.114±0.019 ab
EB Treated	0.044±0.013 a	0.141±0.009 a
CB Treated	0.04±0.007 a	0.12±0.011 ab
WB Treated	0.056±0.01 a	0.131±0.014 ab
EB Untreated	0.046±0.006 a	0.138±0.019 a
CB Untreated	0.04±0.004 a	0.104±0.009 b
WB Untreated	0.046±0.003 a	0.143±0.017 a

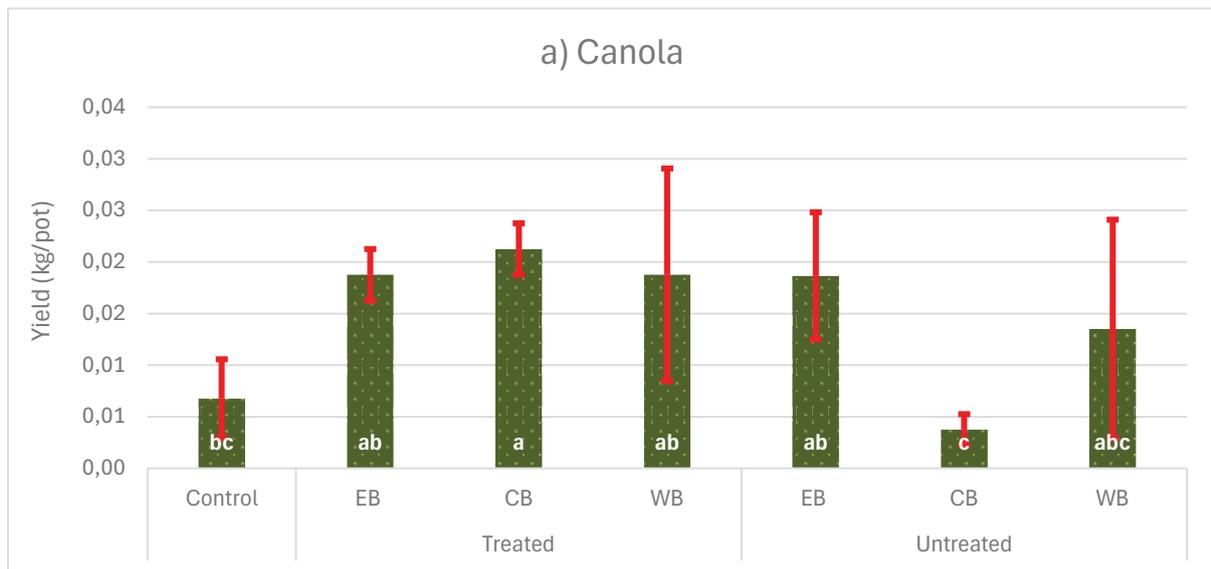


Figure 2.6. Average yield of a) canola and b) oat irrigated with real mine waters.

2.3.2.2 Summer crops

Maize irrigated with mining-influenced waters produced 0.074-0.104 kg vegetative biomass per pot (kg/pot), while the control treatment produced 0.1 kg/pot (Table 2.11). Soybean irrigated with the mining-influenced waters produced 0.053 to 0.057 kg/pot, while the control yielded 0.054 kg/pot. Sweet sorghum irrigated with the mining-influenced waters produced 0.074 to 0.09 kg/pot, while the control yielded 0.054 kg/pot. Overall, irrigation with the Witwatersrand Goldfields mine water did not significantly reduce summer crop biomass production, and there were no significant differences in biomass production between crops irrigated with treated and untreated mine water.

Table 2.11. Mean aboveground dry mass and yield of maize, soybean, and sweet sorghum irrigated with real mine water. Means with the same letter are not significantly different (p-value = 0.0198). Units are kg/pot.

Treatment	Maize	Soybean	Sweet Sorghum
Control	0.1±0.023 a	0.054±0.005 a	0.095±0.005 a
EB Treated	0.092±0.015 a	0.053±0.002 a	0.079±0.013 a
CB Treated	0.104±0.027 a	0.057±0.011 a	0.09±0.005 a
WB Treated	0.074±0.006 a	0.055±0.009 a	0.079±0.019 a
EB Untreated	0.078±0.009 a	0.054±0.005 a	0.081±0.012 a
CB Untreated	0.093±0.022 a	0.054±0.005 a	0.082±0.01 a
WB Untreated	0.097±0.023 a	0.054±0.005 a	0.074±0.008 a

Maize irrigated with the mining-influenced waters yielded 0.032-0.098 kg grain/pot while the control treatment yielded 0.064 kg/pot (Figure 2.7). There were no significant differences in yield between the mine water treatments, except for maize irrigated with treated EB mine water, which had a significantly lower yield than that irrigated with untreated WB mine water, which was the highest yielding treatment. An analysis of the macro elements in the vegetative plant material indicated that maize irrigated with treated EB had a very high sodium concentration, which may explain the yield reduction (Table 2.12). Excessive accumulation of Na in plant tissue is known to decrease biomass accumulation and yield (Santiago-Rosario, et al., 2021). Given that the EB water did not have significantly higher sodium concentrations than the other waters, the source of the high concentrations in the plant material remains undetermined.

Soybean irrigated with the mining-influenced waters yielded 0.027 to 0.033 kg seed/pot, while the control yielded 0.039 kg/pot. Soybeans irrigated with mine waters from the CB and untreated EB mine water had significantly lower yields than the control. The results obtained in this trial differed from those in the first trial, which used synthetic mine waters. This suggests that there may be constituents in the real mine waters that the crop is sensitive to that were absent from the synthetic mine waters.

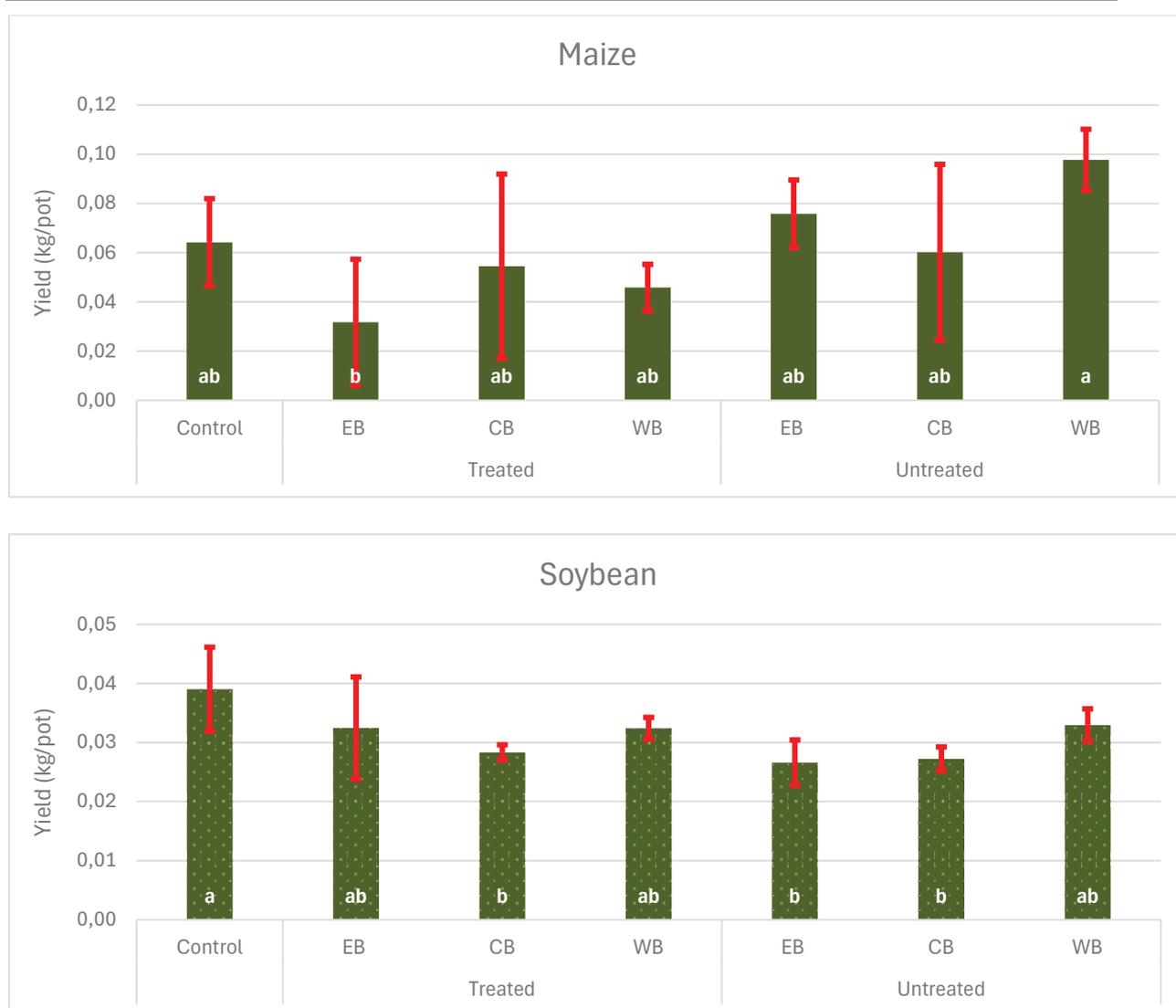


Figure 2.7. Average yield of a) maize and b) soybean irrigated with real mine waters. Error bars show the standard deviation, and the letters show differences in statistical significance.

Table 2.12 Sodium and macronutrient concentrations in the aboveground vegetative plant material of maize in mg/kg on a dry mass basis

Treatment	Na	N	Ca	Mg	K	S	P
Control	284	4000	4900	2000	12900	600	1600
EB Treated	2942	4900	3800	5200	10500	1600	900
CB Treated	405	4700	2400	3900	11300	1000	1600
WB Treated	1108	5800	3000	4400	12300	1400	1800
EB Untreated	1753	4000	3300	4500	15900	1200	500
CB Untreated	319	4700	2800	4600	12900	1200	1000
WB Untreated	626	3100	2500	4600	14300	1100	800

2.3.3 Food and feed safety of crops irrigated with mine waters

Consumption safety is generally not at the forefront of most crop production or agronomic research. However, for this research, it was seen as an important aspect to investigate, mainly due to perceived or real concerns that may arise from irrigating with water containing certain trace elements. Local and International food and feed safety regulations cite arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb) as contaminants in food and animal feed (DAFF, 2012, FAO-WHO, 2023). However, the thresholds tend to vary by region. Additionally, certain elements, such as As and uranium (U), which are important in this study, lack commodity-specific numerical thresholds for the crops assessed, posing a challenge for risk assessment. In the absence of commodity-specific thresholds, benchmarks for other food categories could be used; however, these values may be overly conservative or lenient, leading to under- or overestimation of risk.

Another challenge encountered in assessing consumption safety was the reliability of the material analyses. A recurring issue with the analyses was the method and instrument detection limits. This is exemplified in Table 2.13 and Table 2.14. Table 2.13 shows discrepancies in the analysis results for uranium concentrations in oats, indicating that oats irrigated with deionised mine water had higher uranium concentrations than those in some of the mine water treatments. Background noise was cited as a reason for discrepancies in the analysis results. This brought into question the overall reliability of the results. In light of this, a different lab was used for the summer trial analyses; however, this lab had detection limits much higher than the standard food safety thresholds, as shown in Table 2.14.

Generally, crops irrigated with water from the Witwatersrand Goldfields mine waters, especially treated water, are not expected to pose a consumption safety risk. However, given the importance of these risk assessments and their implications, further investigations are required to determine with greater certainty whether crops irrigated with Witwatersrand Goldfields mine waters pose a real safety risk to consumers. This would require resolving the highlighted challenges with the lack of commodity-specific thresholds and the reliability of the analysis. Unfortunately, the scope of these investigations exceeded the available time for this project; therefore, it is highly recommended that this work be undertaken in a follow-on research project.

Table 2.13. Uranium concentrations in oats grain in the initial analysis and after reanalysis. Units are mg/kg on a dry mass basis.

Treatment	Initial analysis	Reanalysis
	Oats	
Control	7.55	<0.01
EB HDS treated	<0.01	<0.01
CB HDS treated	<0.01	<0.01
WB HDS treated	<0.01	<0.01
EB untreated	<0.01	<0.01
CB untreated	<0.01	<0.01
WB untreated	15.66	<0.01

Table 2.14. Cadmium and lead concentrations in maize grain. Units are mg/kg on a dry mass basis.

Treatment	Cd	Pb
Food safety threshold	0.1	0.2
Feed safety threshold	0.5	5
Control	<1.85	<4.95
EB HDS treated	<1.85	<4.95
CB HDS treated	<1.85	<4.95
WB HDS treated	<1.85	<4.95
EB untreated	<1.85	<4.95
CB untreated	<1.85	<4.95
WB untreated	<1.85	<4.95

2.4 CONCLUSION

The glasshouse pot trials conducted with actual mine waters successfully demonstrated the feasibility of irrigating with mine water from the Witwatersrand Basins. The trials indicated that crop responses to irrigation with mine waters vary between different crops. The results suggest that factors other than salinity play a prominent role in the effects of the mine waters on crop productivity. The biomass and yield data indicate that mine water irrigation can be as productive as irrigation with good-quality water if suitable crops are selected. Additionally, crops can be successfully irrigated with untreated mine waters if soils are strategically limed. Crops irrigated with the Witwatersrand Goldfields mine waters, especially the treated waters, are not expected to pose a safety risk to consumers. However, further investigations are required to determine with certainty whether crops irrigated with Witwatersrand Goldfields mine waters pose a real consumption safety risk. The scope of these investigations exceeded the available time for this project; therefore, the uncertainties could not be further resolved. If there are any real or perceived consumption safety risks, this could be addressed by irrigating industrial crops rather than food or feed crops.

CHAPTER 3: POTENTIAL IMPACTS OF LARGE-SCALE MINE WATER IRRIGATION IN THE EASTERN BASIN ON GROUNDWATER AND RECEIVING SURFACE WATER BODIES

Irrigation with mining-influenced water is expected to enhance recharge in irrigated areas and increase the salt load in seepage water, recharging the aquifer. Therefore, irrigation with mine water has the potential to affect the ambient groundwater quantity and quality, and subsequently, the receiving surface water courses via groundwater base flow. To assess these potential influences on the groundwater environment, as well as receiving surface water bodies (via base flow), the development of a numerical groundwater flow and transport model with consideration of surface-groundwater interaction was proposed in three phases:

- Phase 1: Development of a conceptual hydrogeological site model.
- Phase 2: Development of a numerical groundwater model.
- Phase 3: Predictive model simulations to assess the effects of mine water irrigation on the ambient groundwater quality and quantity.

This chapter presents the findings of the predictive model simulations and monitoring requirements, as well as management options outlined.

3.1 CONCEPTUAL SITE MODEL DEVELOPMENT

A desktop study was conducted to collate and review all available groundwater data and reports for the broader area of interest. The review also focused on the available soil, geological and structural information for the study site to develop a defensible conceptual site model (CSM). The main objective of this task was to accurately conceptualise the aquifers, baseline water quality, groundwater levels, flow regimes, and surface-groundwater interactions as a precursor to numerical model development. The conceptual site model followed a source-pathway-receptor approach. In this phase, aquifer vulnerability was identified, and dolomitic areas were delineated to establish “no-go areas”, that is, areas where irrigation cannot be established.

3.1.1 Geology

The project area within the Eastern Basin (EB) is predominantly underlain by litho-stratigraphic units of the Karoo Supergroup (Figure 3.1), overlain along major river courses by Quaternary alluvial deposits. The soil types in the broader model area are expected to be well-drained soils, including (Natural Scientific Services, 2018):

- yellow-brown apedal soil on soft plinthite soils of the Avalon (Av) form usually overlying hydromorphic, weathered rock or unconsolidated material (shallow dystrophic to mesotrophic loam associated with similar soils of the Glencoe form), and
- red, apedal soils of the Hutton (Hu) form overlying weathered and hard rock and various unconsolidated materials (moderately deep dystrophic to mesotrophic loam).

The lithostratigraphic units of the Karoo Supergroup formed during the Late Carboniferous to Middle Jurassic eras from plant assemblages, thick glacial deposits, and extensive flood basalts, with their associated dolerite sills and dykes. Extensive coal deposits establish the economic importance of the Karoo Supergroup. The Karoo Supergroup comprises several subgroups: Dwyka, Ecca, Beaufort,

Drakensberg, and Lebombo. These sub-groups are further divided into formations. In the study area, the geology is characterised by the Vryheid Formation, forming part of the Eccca Group. The Vryheid Formation is mainly of deltaic origin, consisting of upward-coarsening cycles of sedimentary material, including dark-grey, muddy siltstone, sandstone, dark siltstone, and mudstone units, with interbedded coal units of variable thickness. Occasional outcrops of the Dwyka Group occur within the study area, comprising tillite, subordinate sandstone, and shale (Johnson *et al.* 2006).

Dolerite intrusions in the form of sills and dykes are mainly present in the eastern and southern sections of the study area, and post-date the lithologies of the Eccca Group. These dolerite intrusions are often responsible for the devolatilization of the coal adjacent to them. Typically, dolerite sills crop out at the surface, occur very close to the surface, or have been entirely removed by erosion in some places. These sills are usually fine-crystalline, although they can vary in texture from fine to medium.

In addition to the Karoo sediments, Malmani dolomites (Chuniespoort Group) of the Transvaal Supergroup are present within the model, and are most dominantly found along the river plain of the Blesbokspruit. The Malmani Subgroup comprises dolomite, chert, subordinate quartzite, conglomerate, and shale (Eriksson, 2006). Locally, the Malmani dolomites are described in terms of the more permeable chert-rich Monte Christo Formation, which is underlain by the less permeable Oaktree Formation (Groundwater Square, 2018).

Both the Vryheid Formation and the Chuniespoort Group are underlain by the Witwatersrand Supergroup, which is only exposed as small outcrops. Most is covered by younger sedimentary rocks of the Permian Karoo Supergroup strata. Structurally, the Eastern Basin forms a syncline that dips slightly to the southwest (Groundwater Square, 2018). As a result of folding, several phases of faulting and fracturing of the Witwatersrand Supergroup rocks led to the formation of a complex set of tension and compression joints and fractures. Normal and reverse faults and fractures were either reactivated or developed for the first time following this geological event, forming a small-scale graben structure. Due to folding and folding, secondary geological structures cut through the Witwatersrand (Central Rand Group) and Transvaal (Malmani Dolomites) Supergroups, acting as conduits and resulting in hydraulic linkage between the dolomites and the Witwatersrand strata. Various ages of dyke-like or sill-like intrusions occur in the EB, ranging from post Witwatersrand/Transvaal Supergroups (Ventersdorp feeder dykes, Bushveld age intrusions, Pilansberg dyke swarms) to post Karoo (Karoo dolerite sills and dykes) (Groundwater Square, 2018).

Moreover, small outcrops of the West Rand Group are present in the proposed model area, consisting primarily of quartzites and shales and can be subdivided into the Hospital Hill Subgroup, Government Subgroup and Jeppestown Subgroup (McCarthy, 2006). Many of the quartzites are thought to represent shelf sand bodies. Small outcrops of the Hospital Hill Subgroup consist primarily of shallow marine orthoquartzites, distal siltstones and outer-shelf shales and iron-formation. The Government Subgroup is a lithologically diverse sequence containing rocks ranging from conglomerate to iron formation, as well as several diamictite horizons, reflecting a wide range of depositional environments. The East Rand Goldfield hosts the major economic south-bearing horizon, the 1-1.5m thick South Reef composed of conglomerate and quartzite (McCarthy, 2006).



Figure 3.1. Geological map of the conceptual model outline for the Eastern Basin HDS treatment plant irrigation scheme

3.1.2 Hydrogeology

Based on the conceptual hydrogeological understanding of the site, the following hydro-stratigraphic zones are differentiated within the model area:

- Layer I: Sandy loam top and subsoil with a thickness of 1.2 m (based on the analytical plant model IrrigWQ DSS (du Plessis, Annandale & Benadé, 2023) used to approximate the recharge quantity and quality).
- Layer II: Shallow alluvial and weathered aquifer (13.8 m, thickness).
- Layer III: Upper fractured and intergranular Karoo, Witwatersrand and Transvaal Supergroup rocks with a thickness of 35 m.
 - Dolerite intrusions (post Karoo igneous intrusions)
 - Fractured aquifer comprising the Vryheid Formation of the Karoo Supergroup, Turffontein, Government and Hospital Hill Subgroups of the Witwatersrand Supergroup, and Black Reef quartzite of the Transvaal Supergroup
 - Karst aquifer within the dolomites of the Malmani Subgroup of the Chuniespoort Group

3.1.2.1 Unsaturated zone

The primary receptor of the irrigated water forms predominantly the soil and shallow groundwater. Therefore, the model focuses on the shallow weathered aquifer. No provision was made for artificial mine aquifers due to the lack of available data on mine plans in the study area. The groundwater model considers flow and transport processes within the unsaturated zone of around 14 mbgl, with a capillary pressure-saturation relationship (after van Genuchten) typically assigned to loamy sand for the weathered aquifer, and parameters for coarse sand assigned to the fractured and intergranular rocks and dolerites.

3.1.2.2 Saturated zone

The saturated zone of the study area can be distinguished into a shallow weathered-zone aquifer, a deeper fractured and intergranular aquifer, dolerite intrusions, and karst aquifers. The shallow weathered zone aquifer will be the primary receptor and pathway of potential pollution from the irrigation water.

3.1.2.3 Shallow weathered aquifer

The weathered zone of the model area ranges in depth from approximately 3 m to 39 m, with an average thickness of 13.8 m. Karoo sediments (alternating layers of mudstone and sandstone and post-Karoo dolerites), Transvaal dolomites and quartzites, as well as Witwatersrand quartzites, shales, and siltstones, host the unconfined or semi-confined shallow weathered aquifer or hydrostratigraphic zone. Localised perched aquifers may occur on clay layers or lenses. Due to direct rainfall recharge and dynamic groundwater flow through the unconfined aquifer in weathered sediments, the water quality is generally good, but, in the absence of an overlying confining clay layer, it is also vulnerable to pollution. Water intersections in the weathered aquifer are mostly above or at the interface with fresh bedrock (sandstone or sills), where less permeable layers of weathering products and capillary forces limit vertical percolation and promote lateral water movement. Groundwater discharges at the surface as

springs when the flow path is obstructed by less permeable dolerite sills (contact springs) or when the surface topography cuts into the groundwater level, e.g., in drainage lines (free-draining springs).

3.1.2.4 Fractured and intergranular Karoo, Witwatersrand and Transvaal Supergroup aquifer

The deeper fractured and intergranular aquifer is considered a semi-confined aquifer, depending on the prevailing sedimentary succession. The fractured Karoo aquifer consists of various lithologies, including siltstone, shale, sandstone, and coal seams. Similarly, the Witwatersrand and Transvaal aquifer consists of shales, siltstones, quartzites, and conglomerates and is estimated to be 169-189 m thick (GRAIL).

Groundwater flow is governed by secondary porosities such as faults, fractures, joints, bedding planes, and other geological contacts (including coal seams), while the rock matrix itself is considered impermeable. Geological structures are generally better developed in competent rocks like sandstone, which subsequently yield better water than less competent silt- or mudstones and shales. Not all secondary structures are water-bearing due to, e.g., compressional forces from the neo-tectonic stress field overburden, which can close apertures. Groundwater yields are generally low and are expected to range from 0.1 to 0.5 L/s.

The low-permeability dolerite, diabase and syenite dykes and sills specifically confine the underlying fractured rock aquifer. Borehole yield is enhanced within the contact zones between the dolomite and the dolerite intrusions, as well as by the effects of karstification. The dolerite is an aquitard, offering at best very slow transmission. The contact zone between the intrusive and host rocks is also thought to provide preferential flow paths for groundwater.

3.1.2.5 Dolerite intrusions

The Karoo rocks in the project area were intruded by dolerite sills or dykes, with their contact zones with the host rock providing preferential flow paths. In contrast, the dolerite itself is relatively impermeable or semi-permeable (hydraulic conductivity of approximately 1×10^{-8} m/s). This setting promotes groundwater ponding and flow along, but not across the sills and dykes.

3.1.2.6 Karst aquifer system

Karst aquifers form fissures and/or cavities through chemical weathering, mainly from rainfall, and give dolomites an extremely high permeability and storage capacity. Karst aquifers typically have high hydraulic conductivity (<10 m/d) but are highly heterogeneous, with yields ranging from 0.5 to more than 5 L/s. Higher yields are usually associated with higher hydraulic conductivities along cavities or fissures. These aquifers are typically unconfined. Groundwater flow through a karst aquifer is prone to contamination because of the very nature of the karstified host rock: Fissures and bedding partings in the rock are enlarged by chemical dissolution over time (often related to previous/geological drainage elevations) and provide preferential flow paths, through which water is transferred rapidly and almost unfiltered from input points. The enlarged fractures and bedding partings are responsible for a very heterogeneous distribution of permeability within the karst aquifer.

3.1.2.7 Hydraulic conductivity

The hydraulic conductivities determined in previous studies for the various hydrogeological units in a similar hydrogeological setting are indicated in Table 3.1 (iLEH, 2016). An average hydraulic conductivity of 0.12 m/d was estimated for the different lithologies. The storativity for the quaternary catchments C21D and C21E is estimated at 2.19×10^{-3} % and 9.32×10^{-4} %, respectively (GRAII).

Table 3.1: Summary of hydraulic conductivities K from previous studies conducted (source: iLEH, 2016)

Geology	No of sample points	Average K		
		Average depth m	m/d	m/s
Weathered chert	2	8.7	0.69	8.0E-06
Weathered dolerite	15	11.3	0.20	2.3E-06
Weathered dolerite and dolomite	7	14.0	0.11	1.3E-06
Weathered dolomite	12	15.7	0.11	1.3E-06
Weathered dolomite and chert	1	13.5	3.00	3.5E-05
Weathered dolomite and wad	8	11.9	0.37	4.3E-06
Weathered lava	1	8.0	0.13	1.5E-06
Weathered lava and dolerite	1	15.9	0.04	4.6E-07
Weathered quartzite	2	9.2	0.02	2.3E-07
Weathered shale	1	7.5	0.06	6.9E-07
Wad	1	6.3	0.01	1.2E-07
Fresh dolerite	5	7.9	0.11	1.3E-06
Fresh dolomite	2	19.1	0.14	1.6E-06
Geometric Mean			0.12	6.2E-07

3.1.3 Water quality

3.1.3.1 Groundwater quality

Groundwater quality data of the study area were retrieved from the Department of Water and Sanitation (DWS). The available groundwater quality data was limited to only three monitoring boreholes (182740, 183712 and 1000014608) obtained during the past 20 years, in addition to the four monitoring boreholes (EBH-01, EBH-02, EBH-03, and EBH-04) at the HDS treatment plant, and further three shallow groundwater monitoring boreholes (AECBH01, AECBH13(A), and CEN371(A)) as part of the AMD sludge disposal monitoring programme (Exigo, 2020) (Figure 3.2).

Median water quality values of the ten monitoring boreholes for selected parameters were compared to the South African National Standards for Drinking Water (SANS 241:2015), and the groundwater quality reserves (DWS, 2018) and classes of the quality of domestic water supply (WRC, Volume 1, 1998) for the respective catchment, where available, as well as the DWAF guidelines for irrigation (Table 3.2).

Table 3.2 Quaternary catchment details of available monitoring boreholes

BH ID	Catchment	WQR / RQO
EBH-01	C21E	WQR
EBH-02	C21E	WQR
EBH-03	C21E	WQR
EBH-04	C21E	WQR
AECBH01	C21E	WQR
AECBH13 (A)	C21E	WQR
1000014608	C21D	WQR
CEN371 (A)	C21D	WQR
182740	C21D	WQR
183712	B20A	not available

With regards to the SANS 241:2015 drinking water standards, only boreholes AECBH13(A) and 183712 showed several exceedances for the following parameters (Table 3.3 and Table 3.4):

- Shallow groundwater monitoring borehole AECBH13(A) is located approximately 2.3 km northeast of the HDS treatment plant and exceeded the SANS (241:2015) standards for Ca, Mg, SO₄, EC and TDS.
- Borehole 183712, approximately 34.1 km northeast of the HDS treatment plant, exceeded the SANS (241:2015) standards for Cl, F, Na, EC and TDS.

Elevated sulphate concentrations (1177 mg/L) in borehole AECBH13(A), together with increased Ca and Mg concentrations likely due to buffering processes of carbonaceous material, clearly indicate that the shallow groundwater is affected by the former gold mining activities (including potential seepage from discard dumps) in the area. Borehole 183712 is located on the far northeastern model boundary of the study area in a farming environment. The high Cl and Na concentrations in the groundwater, compared with those in the remaining monitoring boreholes, suggest a deeper, older, stagnant groundwater source from the sodium- and chloride-rich Karoo sediments. At the HDS treatment plant, on-site monitoring borehole EBH-04 depicts generally higher median values of the selected groundwater quality parameters compared to the other three monitoring sites, including sulphate and TDS concentrations of 195 mg/L and 655 mg/L, respectively (Table 3.3).

Based on available groundwater quality classes and reserve data for catchments C21D and C21E, none of the boreholes exceeded the catchment courses: Class 0 for catchment C21D and Class 1 for catchment C21E. However, the stringent groundwater quality reserves were exceeded for most parameters in the majority of boreholes (Table 3.3 and Table 3.4). Only borehole AECBH01 showed a single minor water-quality reserve exceedance for Ca.

According to the target water quality ranges stipulated in the South African water quality guidelines (DWAf) for agricultural use: irrigation (DWAf, 1996), exceedances were observed for Cl, F, and EC in borehole 183712. In borehole EBH-02, the pH and EC values exceeded the target water quality range for irrigation (DWAf, 1996), and the Target water quality range for Mn was exceeded in several boreholes, including EBH-01, EBH-03, EBH-04, AWCBH01 and AECBH13 (A) (Table 3.3 and Table 3.4).

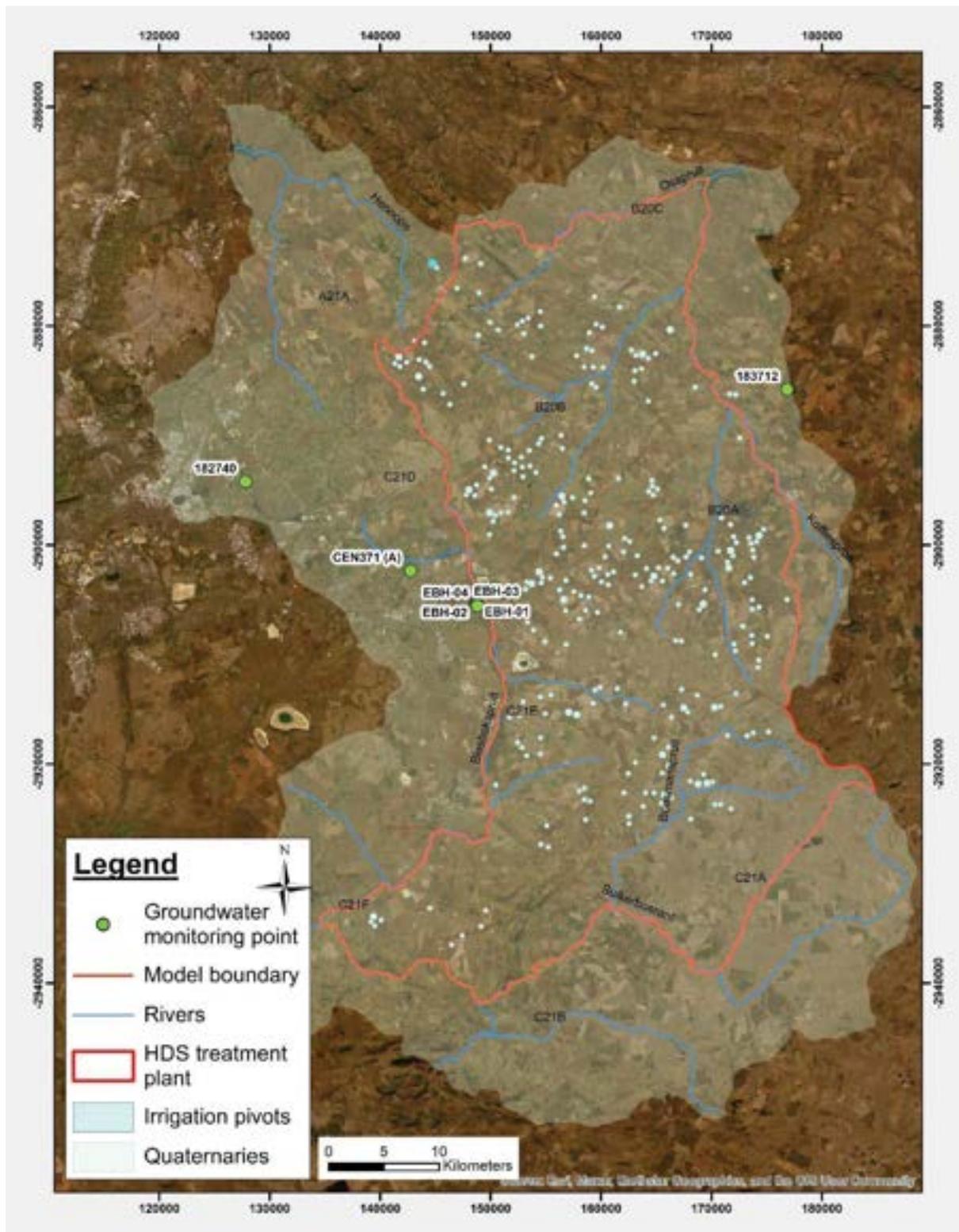


Figure 3.2. Groundwater monitoring points into the broader study area

Table 3.3 Median groundwater quality of the DWS and HDS treatment plant monitoring boreholes at the study site

Site name	Date	pH	EC	TDS	Alkalinity	Ca	Mg	K	Na	SO ₄	Cl
		pH	mS/m	mg/L	mg/L CaCO ₃	mg/L					
SANS 241:2015		≥5.0 – ≤9.7	170	1200		150	70	50	200	500	300
Groundwater Quality Reserve-Quaternary Catchment C21D# (Class0)		(5.0-9.5) 8.1	(<150) 30			(<150) 21	(<70) 12	(<50) 2.4	(<200) 15	(<400) 7	(<200) 9
Groundwater Quality Reserve-Quaternary Catchment C21E (Class 1)		(5.0-9.5) 8.3	(<150) 57			(<150) 44	(<70) 23	(<50) 11	(<200) 29	(<400) 36	(<200) 32
SA WQG 1996: Irrigation		6.5-8.4	40	–	–	–	–	–	–	–	100
EBH-01	2019-2022 (30)	7.6	63	424	197	61	30.5	13.3	24	92	48
EBH-02	2019-2022 (30)	8.6	45	277	65	5	9.9	6	75	9	97
EBH-03	2019-2022 (30)	7.6	73	433	234	47	25.8	3.6	76	23	94
EBH-04	2019-2022 (30)	7.6	95	655	221	93	58.1	5.6	32	195	80
AECBH01	2016-2020 (8)	7	28	183	66	26	13.8	4.7	12	29	27
AECBH13 (A)	2016-2020 (8)	7.7	280	2175	503	336	197.5	18.5	120	1177	66
1000014608#	2006-2024(22)	8.2	107	786	291	77	52.7	10.2	69	51	125
CEN371 (A)#	2016-2020 (8)	7.8	69	472	132	79	44	2	19	223	19
182740#	2004-2024 (6)	8.1	136	1168	279	74	36.2	15.9	56	67	83
183712	2004-2024 (31)	7.8	422	2271	32	96	0.8	10.2	751	2	1288

Table 3.4 Median groundwater quality of the DWS and HDS treatment plant monitoring boreholes at the study site (continued)

Site name	Date	NH ₄ -N mg/L N	NH ₃ -N	o-PO ₄ as P mg/L	Al mg/L	Fe	F	Mn	U
SANS 241:2015			1.5		0.3	2	1.5	0.4	<0.03
Groundwater Quality Reserve-Quaternary Catchment C21D# (Class0)							(<1.0) 0.13		
Groundwater Quality Reserve-Quaternary Catchment C21E (Class 1)							(<1.0) 0.19		
SA WQG 1996: Irrigation		–	–	–	5	5	2	0.02	0.01
EBH-01	2019-2022 (30)	0.17	0.003	0.047	<0.002	<0.004	0.13	0.04	
EBH-02	2019-2022 (30)	0.68	0.051	0.041	<0.002	<0.004	0.13	<0.001	
EBH-03	2019-2022 (30)	0.12	0.003	0.032	<0.002	<0.004	0.29	0.21	
EBH-04	2019-2022 (30)	0.28	0.01	0.036	<0.002	<0.004	0.36	0.311	
AECBH01	2016-2020 (8)	0.06	<0.005		0.007	<0.004	–	0.022	<0.015
AECBH13 (A)	2016-2020 (8)	2.24	0.027		0.006	<0.004	–	0.725	<0.015
1000014608#	2006-2024(22)	0.03		0.01	0.034	0.013	0.37	0.005	
CEN371 (A)#	2016-2020 (8)	0.06	0.005		0.004	<0.004	–	0.002	<0.015
182740#	2004-2024 (6)	0.03		0.037	0.1	0.013	0.3	0.013	
183712	2004-2024 (31)	0.63		0.01	0.015	0.01	5.26	0.006	

3.1.3.2 Surface water quality

Five surface water monitoring points (ESW-01 to ESW-05) in the vicinity of the HDS treatment plant were sampled and assessed along the Blesbokspruit and one tributary since 2015. ESW-01 is located approximately 4 km northwest of the plant and upstream in the Blesbokspruit. ESW-02 and ESW-04 are situated on a tributary of the Blesbokspruit. The tributary joins the Blesbokspruit from the west at a location south of the Grootvlei Tailings Storage Facility (TSF), upstream from the Plant Discharge Effluent. Monitoring point ESW-03 is located downstream of the HDS treatment plant, where the effluent discharges into the Blesbokspruit River. Monitoring point ESW-05 was added as a monitoring site in 2017, and is located on the eastern bank of the Blesbokspruit, upstream of the EB HDS treatment plant but downstream of the old TSF (Exigo, 2020). In addition to the HDS treatment plant surface water monitoring points, three in-stream surface water monitoring points (C2H149Q01, C2H177, and C2H133Q01) are currently monitored along the Blesbokspruit in catchment C21E by the DWS (Figure 3.3).

The median quality of the surface water data for each monitoring point was compared to the Resource Quality Objectives (RQO) for the Blesbokspruit Catchment, C21E (DWS, 2013). Results indicated the following exceedances of the RQO for catchment C21E (Table 3.5 and Table 3.6):

- Monitoring point ESW-02 exceeded the median values for parameters NH₄-N, ortho PO₄ and COD.
- Monitoring point ESW-05 exceeded the median concentration for ortho PO₄.
- Monitoring point ESW-06 exceeded the median value for EC.
- Monitoring point C2H149Q01 exceeded the median values for SO₄ and EC.
- Monitoring point C2H177 exceeded the median concentration for ortho PO₄.
- Monitoring point C2H133Q01 exceeded the median value for EC.

The treated EB Effluent is discharged into the Blesbokspruit drainage system. Both the untreated and treated effluent quality were assessed according to the Department of Water and Sanitation, Directive: Effluent Discharge Standards (AMD-DIR-TCTA-01.03.2011), as well as the wastewater limit values applicable to the discharge of wastewater into a water resource, GN665; GG36820 (2013). The following exceedances were noted for the median values of selected parameters for untreated and treated EB Effluent (Table 3.7 and Table 3.8)

- The median EC value and Mn concentration exceeded the wastewater limit (2013) in both untreated and treated EB Effluent.
- Iron exceeded the directive limit (2011) in the untreated EB Effluent.
- Copper and total cyanide (free cyanide limit was used for comparison purposes) concentrations in the treated EB Effluent exceeded the wastewater limit (2013).
- Uranium concentrations in the untreated EB Effluent exceeded the directive limit (2011).

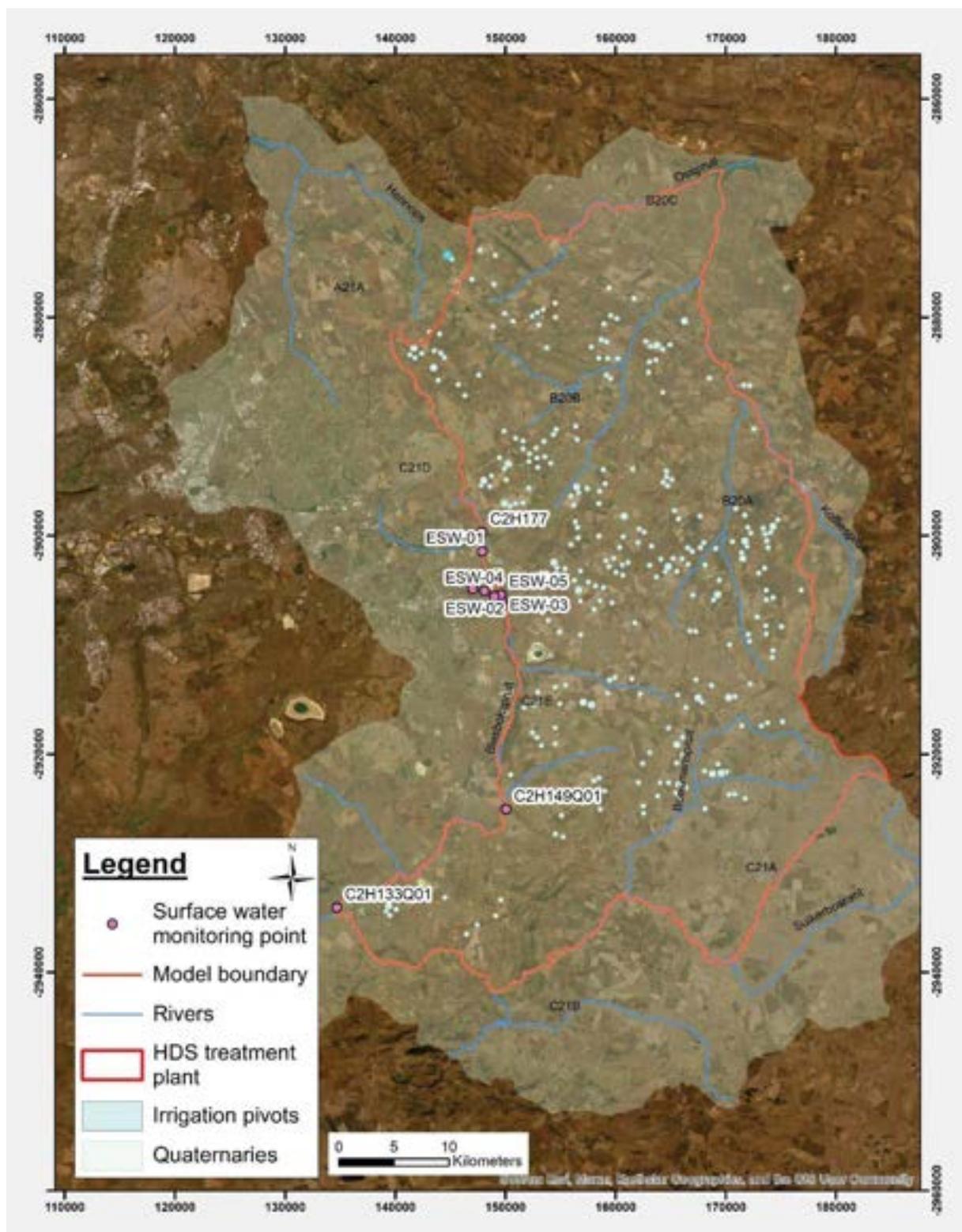


Figure 3.3: Surface water monitoring points within the study area

Table 3.5. Median surface water quality compared to resource quality objectives of catchment C21E (exceedances of unacceptable limits highlighted in red)

Site name	No. of measurements	pH	EC	TDS	Alk.	HCO ₃	Ca	Mg	K	Na	SO ₄	Cl
		pH	mS/m	mg/L	mg/L CaCO ₃	mg/L CaCO ₃			mg/L			
	Ideal	6.5-8.5	<45					<8		<70	<150	<80
	Acceptable		45-70					Aug-30		70-100	150-300	80-150
	Tolerable		70-120					30-70		100-150	300-500	150-200
	Unacceptable	<6.5;>8.5	>120					>70		>150	>500	>200
ESW-01	(2015-2022) 63	7.7	69	462	165	161	54	17	11	67	102	65
ESW-02	(2015-2022) 63	7.7	56	326	190	189	47	17	7	35	54	29
ESW-03	(2015-2022) 63	7.8	112	774	145	143	108	34	12	96	343	75
ESW-04	(2015-2022) 62	7.8	63	402	198	195	54	19	9	48	65	44
ESW-05	(2015-2022) 39	8.1	84	564	173	170	75	24	12	83	189	71
ESW-06	(2015-2022) 5	7.9	128	796	196	194	117	41	13	93	340	71
C2H149Q01	(1996-2024) 165	8.1	162	1279	200		176	51	13	134	540	130
C2H177	(1996-2021) 137	7.4	64	388	147		32	13	9	54	66	64
C2H133Q01	(1993-2024) 250	8.3	125	777	160		77	31	12	110	205	125

Table 3.6. Median surface water quality compared to resource quality objectives of catchment C21E (exceedances of unacceptable limits highlighted in red) (continued)

Site name	No. of measurements	NO ₃ -N	NH ₄ -N mg/L	o-PO ₄ as P	Total Hardness mg/L CaCO ₃	COD	SS	Al	Fe mg/L	F	Mn
Ideal		<0.5	0.1	<0.2		<20	<20		0.1	<0.19	<0.2
Acceptable		0.5-3.0	0.1	0.2		20-35	20	<0.3	0.1	0.19-0.70	0.2
Tolerable		3.0-6.0	1.5	0.4		35-55	30	0.3	0.5	0.70-1.00	0.5
Unacceptable		>6.0	5	0.6		>55	55	0.5	1	>1.00	1
ESW-01	(2015-2022) 63	1.34	0.78	0.45	207	53	12	<0.002	<0.004	0.3	0.06
ESW-02	(2015-2022) 63	0.25	6.72	0.6	186	65	4	<0.002	<0.004	0.31	0.23
ESW-03	(2015-2022) 63	0.93	0.17	0.5	411	42	7	<0.002	<0.004	0.27	0.04
ESW-04	(2015-2022) 62	0.49	1.17	0.35	217	54	5	<0.002	<0.004	0.31	0.17
ESW-05	(2015-2022) 39	0.59	0.16	0.62	281	50	6	<0.002	<0.004	0.3	0.02
ESW-06	(2015-2022) 5	0.61	0.04	0.45	380	44	6	<0.002	<0.004	0.13	0.11
C2H149Q01	(1996-2024) 165	0.1	0.05	0.38						0.3	
C2H177	(1996-2021) 137	0.8	1.2	0.65						0.3	
C2H133Q01	(1993-2024) 250		0.06	0.14						0.31	

Table 3.7. EB Effluent quality compared to wastewater limits (2013) and directive limits (2011) from 2018 to 2024 (in mg/L)

EB Effluent	No. of measurements	pH	EC (mS/m)	Acidity as CaCO ₃	Alkalinity as CaCO ₃	TDS	Ca	Mg	K	Na	SO ₄	Cl	o-PO ₄ as P	Turbidity (NTU)	SS
Wastewater Limit (2013) ^a		5.5-9.5	150	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10	N/A	25
Directive Limits ^b		6.5-9.5	450	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3000	N/A	N/A	<30	N/A
untreated	34	6.5	275	113	340	2362	335	110	13.2	187	1199	112	<0.2	362	–
treated	34	7.9	258	8.35	270	2231	320	101	12.7	191	1191	113	0.2	6.81	2.8

Table 3.8 EB Effluent quality (selected trace elements) compared to wastewater limits (2013) and directive limits (2011) from 2018 to 2024 (in mg/L)

EB Effluent	No. of measurements	Cu	Al	Fe	Mn	Ni	U	B	free CN	F
Wastewater Limit (2013) ^a		0.01	N/A	0.3	0.1	N/A	N/A	N/A	0.02	1
Directive Limits ^b		N/A	<1	<1	<10	N/A	0.05	N/A	N/A	N/A
untreated	34	<0.01	0.05	80.85	4.09	0.0425	0.056	0.2645	–	0.55
treated	34	0.027	0.05	0.0825	1.75	0.0225	0.032	0.2795	0.07 (total)	0.45

3.1.4 Groundwater facies

Median surface- and groundwater monitoring results were plotted on a Piper diagram to determine the water type and major chemical characteristics (Figure 3.4). Boreholes EBH-03, 100014608, 182740, as well as surface water monitoring sites ESW-02 and ESW-04, are classified as Ca-Mg-HCO₃ water type. The bicarbonate dominance in these samples results from CO₂ equilibration of rainwater with the atmosphere and from percolating rainwater equilibrating with the further CO₂-enriched soil atmosphere as a result of the decay of plant humus, litter, and other organic substrates. Water seeps through the soil and vadose zone, which are also rich in carbon dioxide from the weathering of carbonate minerals, which, in turn, dissolve as bicarbonate into the water. The bicarbonate-enriched water signature indicates potential fresher, recently recharged groundwater (EBH-03, 100014608, and 182740), as well as recent (sub-) surface runoff and groundwater discharge into the river (ESW-02 and ESW-04).

The mixed cation signatures (calcium/magnesium versus sodium) can be attributed to cation exchange reactions that occur during groundwater evolution within the soil and rock matrix. Borehole EBH-02 and 183712 are characterised by a Na-Cl-SO₄ water facies, and represent highly mineralised, stagnant groundwater that equilibrated with sodium and chloride-rich sediments of the Karoo Supergroup, or, in the case of borehole EBH-02, likely some contribution of sulphate-contaminated mine water.

Both the treated and untreated EB Effluent, as well as monitoring boreholes CEN371 (A) and AECBH13 (A), show a dominant Ca-Mg-Cl-SO₄ water facies, typically for mineralised waters affected by mining activities such as coal and gold mining, exhibiting acid rock drainage (ARD) buffered by calcium carbonate. Sulphate is a typical product of acid rock drainage due to pyrite oxidation from waste rock dumps and underground mine voids filling up with oxygen-rich water. Sufficient sulphate contamination may lead to gypsum equilibrium in concentrated solutions.

Boreholes EBH-04, EBH-01, and AECBH01 represent a mixed water facies being dominated by Ca-Mg-SO₄-HCO₃, suggesting that recently recharged fresh groundwater is mixed with mineralised sulphate-rich mine water. Surface water monitoring points ESW-01, ESW-03, ESW-05 and ESW-06, as well as C2H177, C2H133Q01 and C2H149Q01 are characterised by mixed water facies including Ca-Na-Mg-SO₄-HCO₃ suggesting the mixing of regional water types Ca-Mg-HCO₃ or Na-HCO₃ facies resulting from CO₂ equilibration of surface water with the atmosphere and both groundwater discharge of recently recharged and deeper, older stagnant groundwater originating from the sodium and chloride-rich Karoo sediments. In addition, surface water monitoring sites ESW-06, ESW-03, and C2H149Q01 showed an increase in sulphate content relative to the other major water components, similar to that observed in the EB effluent. This suggests that these surface water monitoring sites are influenced by sulphate-enriched mine water discharge in the area, especially for monitoring site ESW-03, which is located downstream of the EB effluent discharge into the Blesbokspruit and monitoring site C2H149Q01, further downstream within the Blesbokspruit catchment C21E.

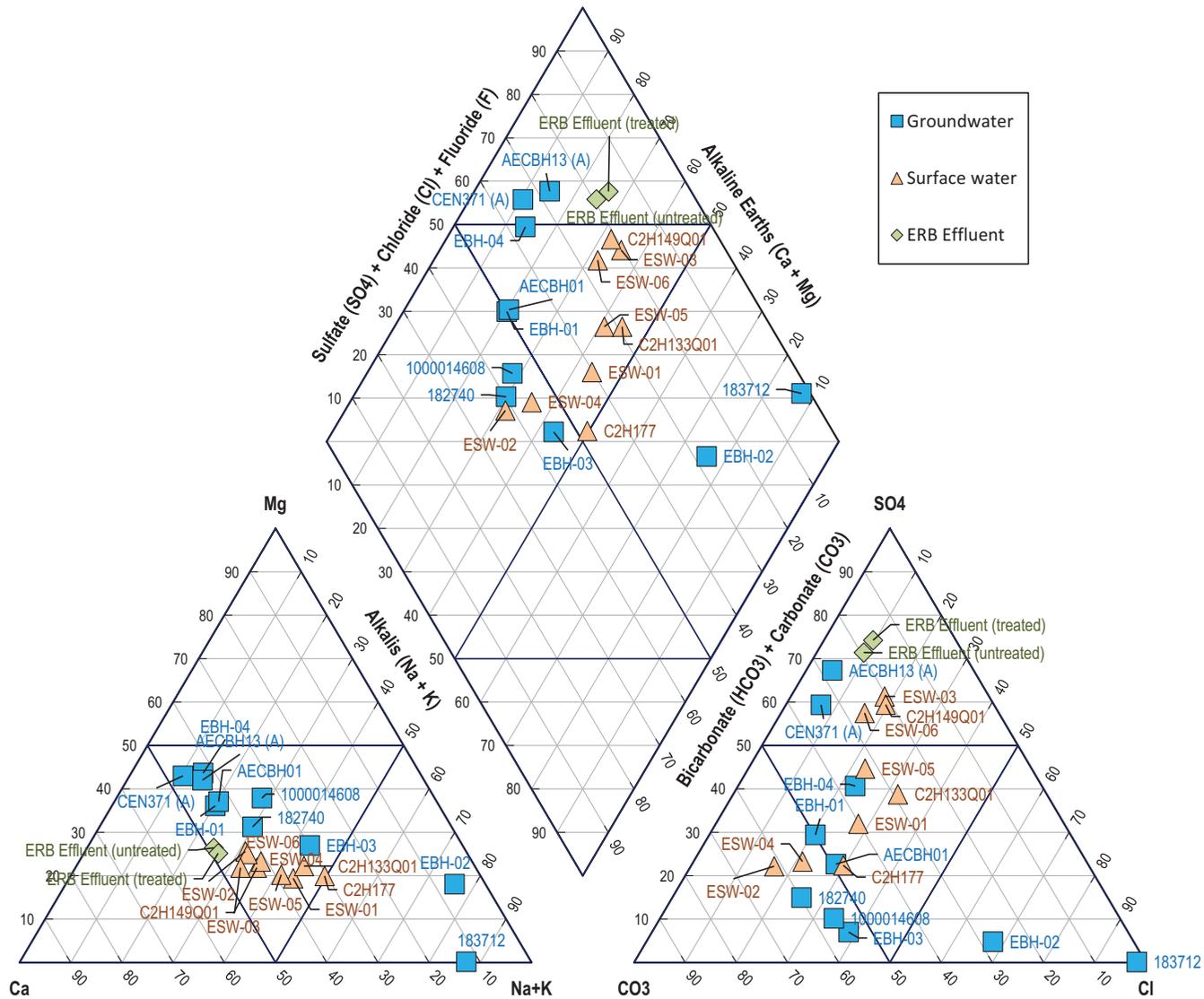


Figure 3.4: Piper diagram indicating the median groundwater, surface water and effluent quality at the EB HDS treatment plant (from 2015 to 2024)

3.1.5 Aquifer classification

According to the Hydrogeological Map (1:500 000) series, the regional hydrogeology of the conceptual model area is mainly characterised by an ‘intergranular and fractured aquifer’ Vryheid Formation of the Karoo Supergroup with an expected potential yield of 0.1–0.5 L/s. A microfractured matrix in the fractured Karoo aquifers provides storage capacity with limited groundwater movement, while secondary features, such as fractures/faults and bedding planes, enhance groundwater flow.

The intergranular aquifer is associated with the river alluvial and Quaternary sand deposits. Smaller localised pockets are characterised as a major ‘karst aquifer’, especially along the Blesbokspruit riverbed, with a typical potential yield of > 5 L/s (Figure 3.5). The karst aquifer is associated with the dolomites of the Malmani Subgroup in the Transvaal Basin. Based on the aquifer classification map (Parsons and Conrad, 1998), the aquifer system underlying the project area is regarded as a “major aquifer” (Figure 3.5).

A summary of the classification scheme is provided in Table 3.9. In this classification system, it is important to note that the concepts of Minor and Poor Aquifers are relative and that yield is not quantified. Within any specific area, all classes of aquifers should therefore, in theory, be present.

Table 3.9. Aquifer classification scheme after Parsons and Conrad (1998)

Aquifer	Description
Sole source aquifer	An aquifer used to supply 50% or more of urban domestic water for a given area, for which there are no reasonably available alternative sources, should this aquifer be impacted upon or depleted.
Major aquifer region	High-yielding aquifer of acceptable quality water.
Minor aquifer region	Moderately yielding aquifer of acceptable quality or a high-yielding aquifer of poor-quality water.
Poor aquifer region	An insignificantly yielding aquifer of good quality, or a moderately yielding aquifer of poor quality, or an aquifer that will never be utilised for water supply and that will not contaminate other aquifers.
Special aquifer region	An aquifer designated as such by the Minister of Water

1.1.1 Aquifer Protection Classification

As part of the aquifer classification, a Groundwater Quality Management (GQM) Index is used to define the level of groundwater protection required (Parsons 1995). The point scoring system and classification of the site-specific project area for the irrigation trial plot are presented in Table 3.10.

Table 3.10. Groundwater Quality Management (GQM) Classification System

Class	Points	Project area score
Aquifer System Management Classification		
Sole Source Aquifer System:	6	
Major Aquifer System:	4	
Minor Aquifer System:	2	4
Non-Aquifer System:	0	
Special Aquifer System:	0 – 6	
Aquifer Vulnerability Classification		
High:	3	
Medium:	2	3
Low:	1	

The recommended level of groundwater protection based on the Groundwater Quality Management Classification is calculated as follows:

GQM Index = Aquifer System Management x Aquifer Vulnerability = 4 x 3 = 12 (Table 3.11).

For the wider project area where no karst aquifers are present, a GQM index of 4 can be assigned based on the ratings for the Aquifer System Management Classification.

According to this estimate, a medium-level groundwater protection is required for the intergranular and fractured aquifer. Reasonable groundwater protection measures are recommended to ensure that no cumulative pollution affects the aquifer, even in the long term. For the dolomitic aquifers in the study area, a strictly non-degradation level of protection is required, and no irrigation with untreated and treated mine water should be conducted at these sites. DWS's water quality management objectives are to protect human health and the environment. Therefore, the significance of this aquifer classification is that, if any potential risk exists, measures must be taken to limit its impact on the environment, in this case by protecting the underlying aquifer.

Table 3.11: GQM index for the project area

Index	Level of Protection	Project area
<1	Limited	12
1 – 3	Low Level	
3 – 6	Medium Level	
6 – 10	High Level	
>10	Strictly Non-Degradation	

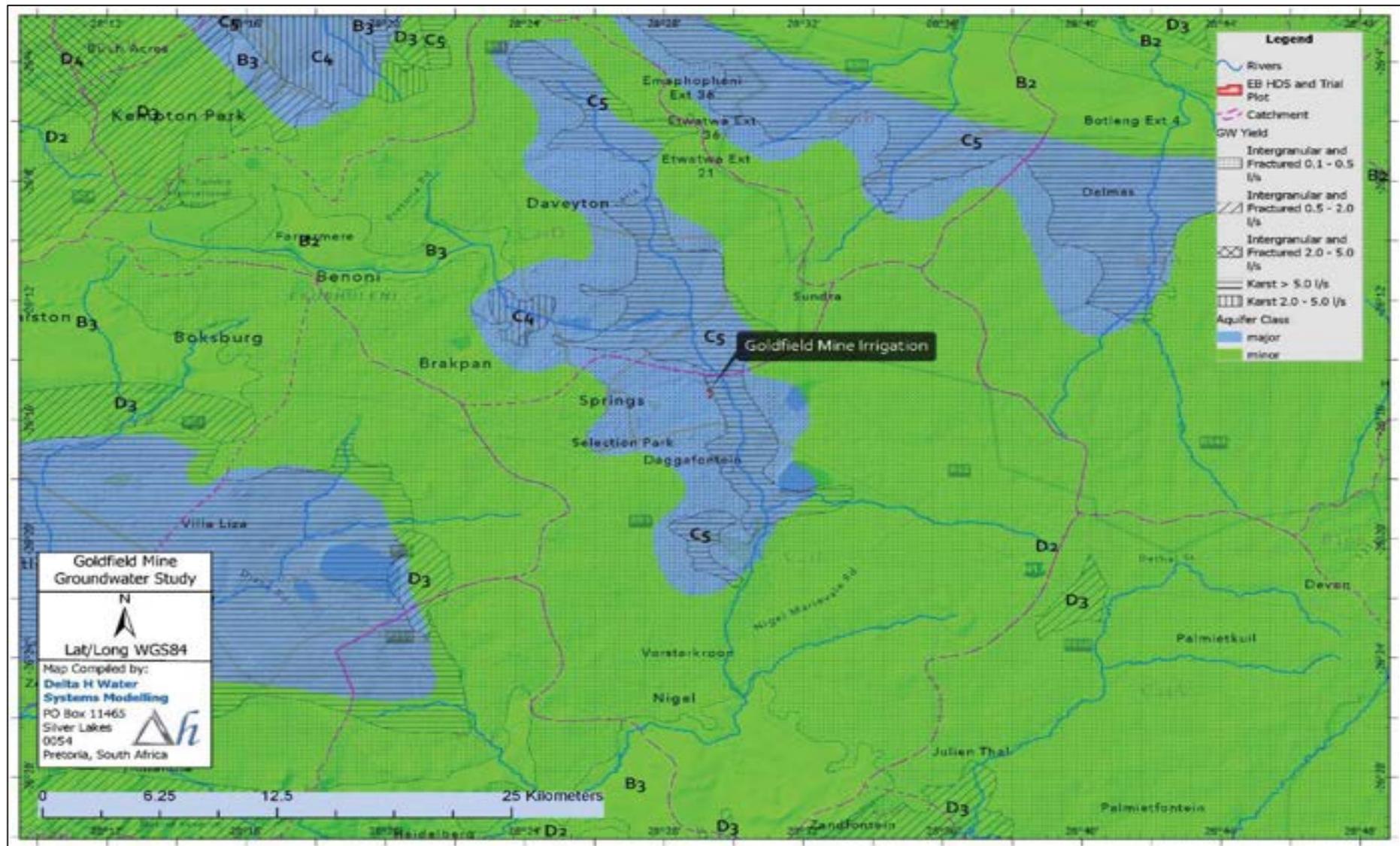


Figure 3.5: Aquifer classification of the proposed model area according to Parsons and Conrad (1998)

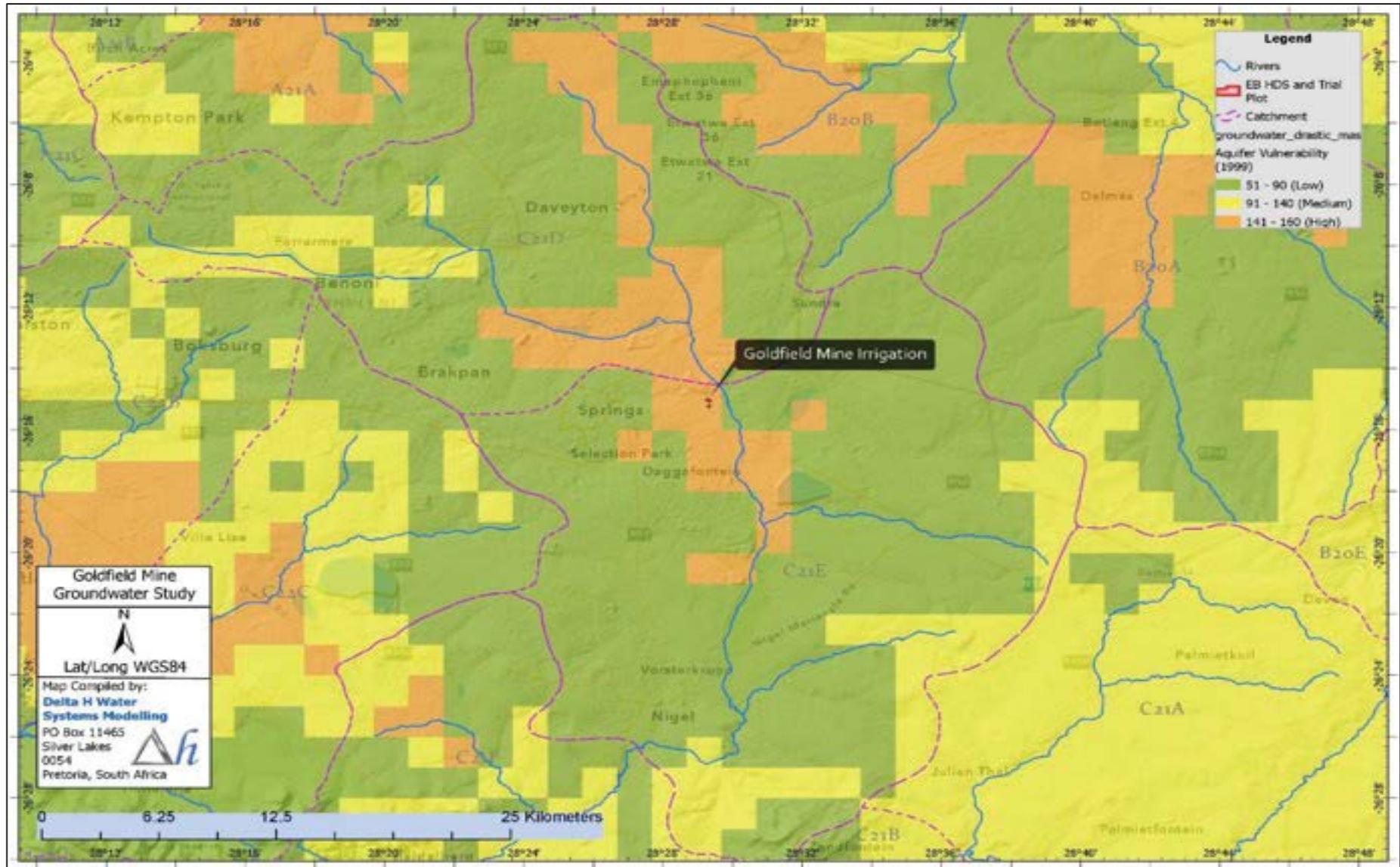


Figure 3.6: Groundwater vulnerability map for the proposed model area of the EB HDS Goldfields irrigation study

3.2 NUMERICAL MODEL DEVELOPMENT

3.2.1 Software choice

The software code chosen for the numerical finite-element modelling work was the 3D groundwater flow model SPRING, developed by the delta h Ingenieurgesellschaft mbH, Germany (König, 2011). SPRING uses the finite-element approximation to solve the groundwater flow equation. This means that the model area or domain is represented by several nodes and elements. Hydraulic properties are assigned to these nodes and elements, and an equation is developed for each node based on the surrounding nodes. A series of iterations is then run to solve the resulting matrix problem, utilising a preconditioned conjugate gradient (PCG) matrix solver for the current model. The model is said to have “converged” when errors reduce to within an acceptable range. SPRING can simulate steady and non-steady flow in aquifers of irregular dimensions.

SPRING solves the stationary flow equation independent of the density for variable saturated media as a function of the pressure according to:

$$-\nabla(K_{ij}\nabla h) = -\nabla\left(K_{perm}\frac{\rho g}{\mu}\nabla h\right) = q = -\nabla\left[\frac{K_{perm}\cdot k_{rel}}{\mu}(\rho g\nabla z + \nabla p)\right] \quad \text{Equation 5}$$

$$\nabla \quad \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$$

q	Darcy flow
K_{ij}	Hydraulic conductivity tensor
ρg	Density · gravity
K_{perm}	Permeability
μ	Dynamic viscosity
k_{rel}	Relative permeability
p	Pressure

The relative hydraulic permeability k_{rel} is hereby calculated as a function of the relative water saturation S_r , which in turn is a function of the effective relative saturation:

$$k_{rel}(S_r) = (S_e)^l \left[1 - \left(1 - (S_e)^{\frac{1}{m}}\right)^m\right]^2 \quad \text{Equation 6}$$

$$S_e = \frac{S_r(p) - S_{res}}{S_s - S_{res}} = \left[1 + \left(\frac{p_c}{p_e}\right)^n\right]^{\frac{1-n}{n}} \quad \text{Equation 7}$$

$S_r(p)$	Relative saturation dependent on pressure
S_e	Effective saturation
l	Unknown parameter, determined by van Genuchten to 0.5

m	equal to $1 - (1/n)$
n	Pore size index
S_{res}	Residual saturation
S_s	Maximum saturation
p_c	Capillary pressure
p_e	Water entry pressure

Solving these equations for the relative saturation as a function of the capillary pressure $S_r(p_c)$ results in the capillary pressure– saturation function according to the Van Genuchten (1980) model as used in SPRING:

$$S_r(p_c) = S_{res} + (S_s - S_{res}) \cdot \left[1 + \left(\frac{p_c}{p_e} \right)^n \right]^{\frac{1-n}{n}} \quad \text{Equation 8}$$

The water entry pressure is a soil-specific parameter, defined as the inverse of $\alpha = 1/p_e$ in the saturation parameters. The density-independent, instationary flow equation for variable saturated media as a function of the capillary pressure (equal to Darcy flow for water saturated media) is given as follows:

$$\rho \left(S_r(p_c) S_{sp} + \theta \frac{\partial S_r(p_c)}{\partial p} \right) \frac{\partial p}{\partial t} + \theta S_r(p_c) \frac{\partial \rho}{\partial t} - \nabla \left[\rho \frac{K_{perm} k_{rel}}{\mu} (\nabla p + \rho g \nabla z) \right] = q \quad \text{Equation 9}$$

The specific pressure-dependent storage coefficient S_{sp} is hereby given as

$$S_{sp} = \alpha(1 - \theta) + \beta\theta \quad \text{Equation 10}$$

α	Compressibility of porous media matrix
β	Compressibility of fluid (water)
θ	Aquifer porosity

The transport equation for a solute in variably saturated aquifers is given as follows:

$$\theta S_r(p_c) \frac{\partial c}{\partial t} + \theta S_r(p_c) v \nabla c - \nabla (\theta S_r(p_c) (D_m \bar{1} + D_d) \nabla c) = qc^* + R_i \quad \text{Equation 11}$$

qc^*	Volumetric source/sink term with concentration c^*
D_m	Molecular diffusion
$\bar{1}$	Unit matrix
D_d	Hydrodynamic dispersion
R_i	Reactive transport processes (sorption, decay, etc.)

The software is therefore capable of deriving quantitative results for groundwater flow and transport problems in the saturated and unsaturated zones of an aquifer.

Stability criteria

To simulate solute transport accurately and comply with applicable numerical stability criteria (Courant number C_r), the time step width must be adjusted for the predictive scenarios.

$$C_r = \left| \frac{v \Delta t}{L} \right| \leq 1 \quad \text{Equation 12}$$

The geometry of the mesh can have an undesirable effect (numerical dispersion) on the simulated spreading of solutes if the elements are too large in relation to the dispersion length. The mesh was therefore designed to comply with the Peclet criteria:

$$L < 2\alpha_l \quad \text{Equation 13}$$

v Flow velocity
 Δt Discrete time step
 L Longest dimension of an element in the direction of flow
 α_l Longitudinal dispersion coefficient

A measure of this ratio is the Peclet number P_e , which should be less than 2 so that the proportion of the non-hyperbolic part of the transport equation dominates:

$$P_e = \left| \frac{v\Delta l}{D} \right| < 2 \quad \text{Equation 14}$$

It describes the ratio of the advective part to the dispersion part (D) with respect to a characteristic length (side length of the elements, Δl). The lower the Peclet number, the fewer iterations are necessary to achieve a pre-defined maximum value of the residuals. Once this dimensionless number exceeds 10, it is no longer guaranteed that the solution converges. An optimal spatial discretisation results in a Peclet number less than 2.

Model History

To assist in the assessment of potential environmental impacts associated with mine water irrigation, Delta H developed, as part of this project, four (4) different numerical groundwater models:

- A local scale model was developed to cover the quaternary catchment surrounding the Eastern Basin HDS water treatment facility to assess mine water irrigation on the envisaged field site. No further work was done on the local-scale model, as the irrigated field test site could not be established.
- Considering the available volume of mine water, the search radius for available irrigation sites was expanded to a 50 km radius around the Eastern Basin HDS water treatment facility. A regional-scale single-layer numerical groundwater model was developed with the specific focus of delineating no-go areas for irrigation with mine water. The no-go areas (Figure 3.7) were delineated using the model by backward calculation of transport times to surface water drainages, i.e., any areas potentially conveying irrigation return flows within one year towards a river course, as well as dolomitic areas were excluded from the considered irrigation areas.
- Following the exclusion of no-go areas and with consideration of logistical constraints, a regional-scale model covering a 30 km radius around the Eastern Basin HDS water treatment facility was developed in Phase 2 of the project, and is supposed to be used for the predictive simulations. However, the finite-element mesh of the model considered only existing irrigation pivots as well as areas (farm boundaries) which could be irrigated (Figure 3.8), but not potential irrigation pivots within these areas.
- The finite-element mesh of the final regional scale (30 km) model was therefore re-developed in the current Phase 3 of the project to reflect the delineated individual 20 ha and 40 ha irrigation pivots and thereby predict potential impacts of return flows from these pivots. The final model is described in the next section.

3.2.2 Model description

3.2.2.1 Model set-up and boundaries

The final finite-element model was set up as a three-dimensional groundwater model. The model domain was slightly reduced from the previous regional-scale (30 km) model area (2 052 km²) by moving the northern model boundary to a river (instead of the quaternary catchment boundary) and now covers a surface area of around 1 958 km². The model domain straddles eight (8) quaternary catchments. While the northern, north-western and a small section of the eastern boundaries follow topographical highs (quaternary catchment boundaries), the remaining model boundaries follow perennial river courses (Figure 3.9). The chosen approach ensures a reliable water balance in the model, with rainfall recharge as the primary driver of groundwater flow.

3.2.2.2 Geometric structure of the model

The model was spatially discretised into 481 235 nodes on four node layers, which make up three element layers with 505 841 elements (triangles and quadrangles) each or a total of 1 517 523 elements (Figure 3.9). The horizontal element size (side length) varies from a minimum of 10 m along certain irrigation pivots to a maximum of 65 m further away from the area of interest and expected steep head or concentration gradients. The spatially variable discretisation of the finite-element model domain enables the accurate incorporation of irrigation pivots and surface water features (rivers) into the regional groundwater model.

According to the conceptual understanding, element layer I represents the soil zone (1.2 m thickness, as used in the IrrigWQ DSS developed by du Plessis, et al. (2017) Layer II, the upper weathered zone (13.8 m thickness) and layer III, the upper fractured aquifer (35 m thickness), within the model domain. The model's final depth is 50 m below ground elevation. Note that this assumption does not suggest the general absence of groundwater flow or transport at greater depth, but a negligible contribution thereof in the context of the study.

3.2.2.3 Boundary Conditions

An overview of the physical features and assigned boundary conditions used in the Goldfields irrigation groundwater flow model is given in Table 3.12.

Table 3.12: Boundary conditions assigned in the groundwater model

Boundary	Natural feature	Assigned boundary condition
Top	Land surface	Rainfall recharge, irrigation return flows
Top, internal and perimeter	Rivers	River lines, no losses allowed
Perimeter (NW and SE section)	Topographic high	No-flow
Bottom	Vertical limit of the active groundwater flow system	No-Flow

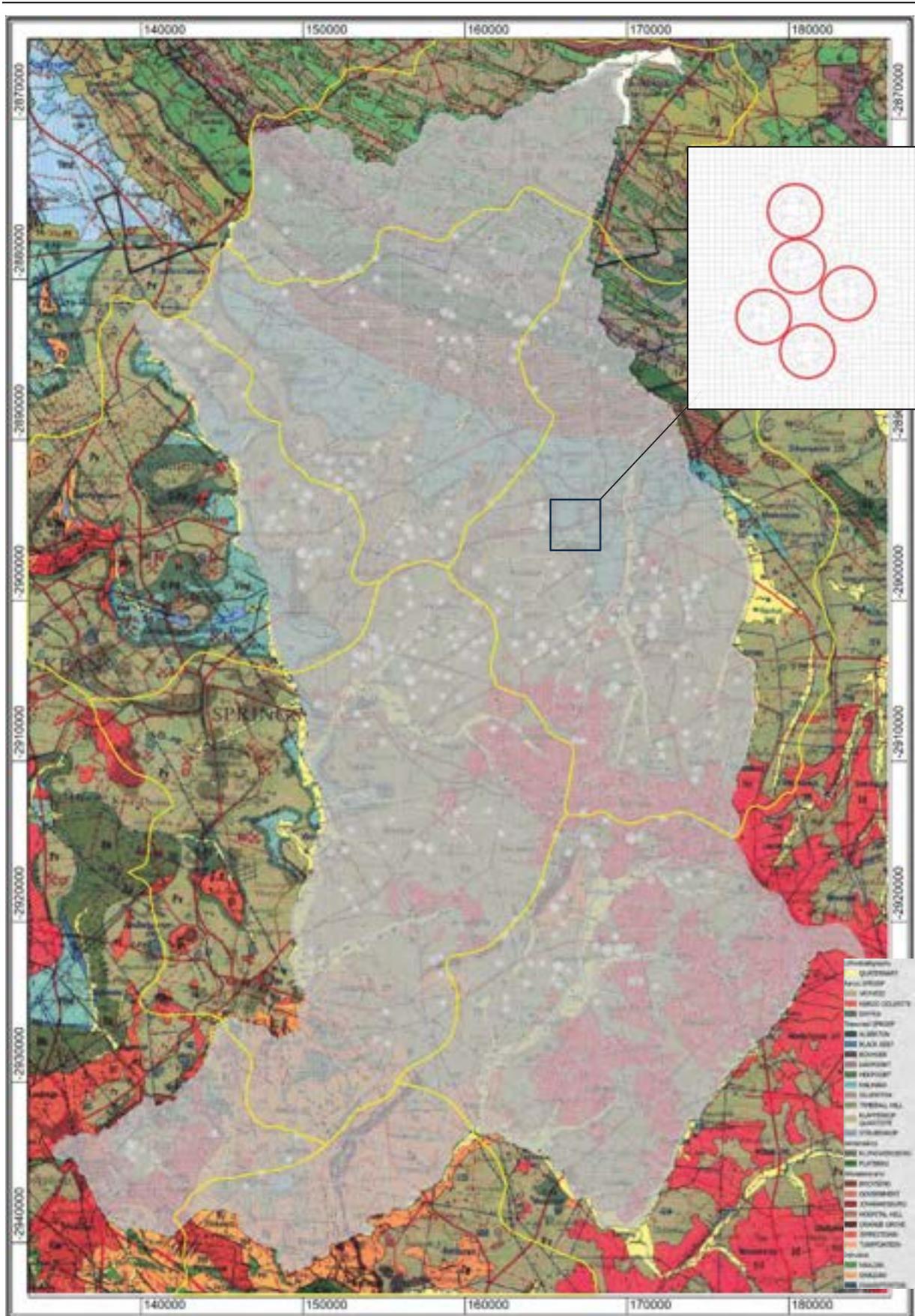


Figure 3.9: Finite element mesh of the final Witwatersrand Goldfields Irrigation Groundwater Model (quaternary catchments indicated in yellow, irrigation pivots in white)

3.2.2.4 Selection of Calibration Targets and Goals

A total of 218 groundwater levels from the National Groundwater Archive were used as calibration targets for the irrigation model. The groundwater levels, as measured in metres below ground level (mbgl), were converted within the model using the assigned (50m x 50m) digital elevation model into metres above mean sea level (mamsl) to ensure alignment with the model elevation.

A plot of the groundwater table against surface elevation data for the 218 boreholes in the model area (Figure 3.10) shows a strong correlation ($R^2 = 0.96$), suggesting a mostly unconfined aquifer system in which shallow groundwater conditions mimic surface topography, with groundwater flowing from higher-lying areas towards lower-lying areas and into drainage systems (natural streams).

A groundwater piezometric map was interpolated from the collated measured water levels using Bayesian interpolation, based on the established correlation between surface topography and groundwater levels. The Bayesian interpolation method uses correlated data to improve the spatial interpolation of the unknown variable, in this case, the groundwater level. As a Universal Kriging algorithm, it relies on a mathematical description of the change (or variance) of a variable with distance, i.e. to what extent neighbouring observations are spatially correlated (Figure 3.11). The semi-variogram model is then used in combination with surface elevation and its correlation with groundwater elevation to provide a qualified estimate to improve the spatial interpolation of water levels.

The interpolated (unconfined) groundwater piezometric map using Bayesian interpolation (Figure 3.12) was subsequently used as the initial heads for the model calibration. While the assigned initial heads facilitate the mathematical convergence of a steady-state model, they do not change the outcome of the model, i.e. the calculated steady-state heads.

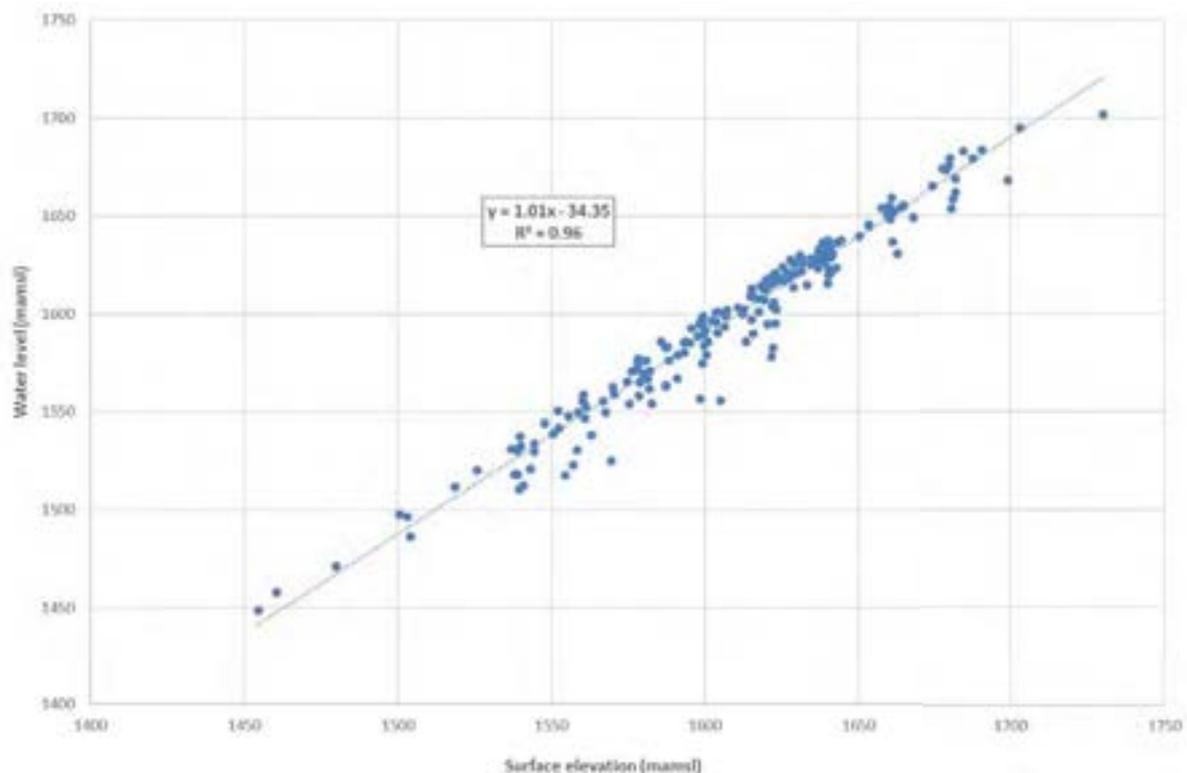


Figure 3.10: Cross-plot of surface and groundwater elevations indicating shallow groundwater conditions mimic surface topography

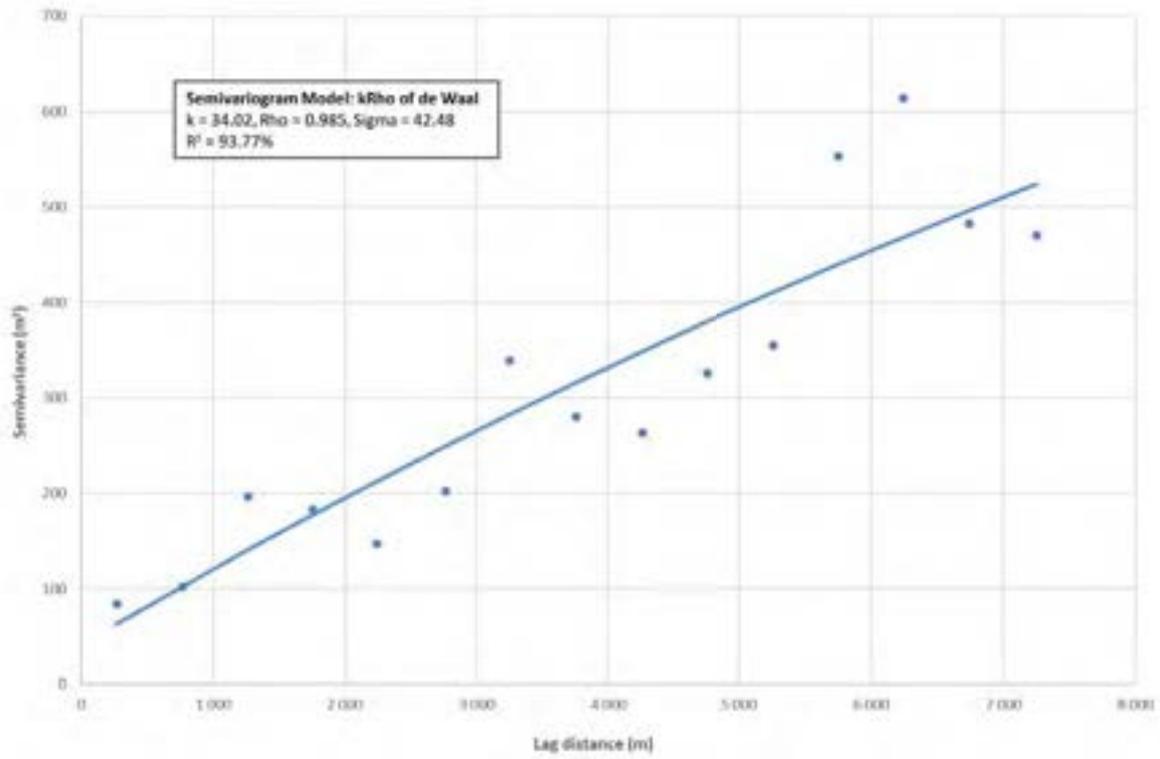


Figure 3.11: Empirical semi-variogram and fitted Bayesian model for the model area

3.2.3 Model parameters

SPRING uses an efficient preconditioned conjugate gradient (PCG) solver for the iterative solution of the flow and transport equation. The closure criterion for the solver, i.e. the convergence limit of the iteration process, was set at a residual below $1e-06$. The Picard iteration, used for the iterative computation of the relative permeability for each element as a function of the relative saturation and capillary pressure, used a damping factor of 0.5 and was limited to 8 iterations. The relative difference between the two computed potential heads (saturated zone) and capillary pressures (unsaturated zone) after seven iterations was generally below acceptable limits of 0.05 m and 0.1 m, respectively.

3.2.3.1 Initial and Assigned Conditions

The initial conditions specified in the steady state flow model were as follows:

- Starting heads as shown in Figure 3.12.
- Horizontal hydraulic conductivities of $1E-06$ m/s for the soil and weathered aquifer zones and $1E-08$ m/s for the upper fractured aquifer.
- Vertical hydraulic conductivities were set at 10% of the horizontal conductivities.
- Effective porosity values were specified as 15% for the soil and weathered aquifer and 8% for the fractured aquifer.

3.2.3.2 Steady State Calibration of Flow Model

The groundwater levels (in metres above mean sea level) measured in 218 groundwater monitoring boreholes within the model domain were used as targets for the steady-state model calibration. Since the modelled groundwater levels are directly related to the assigned recharge rates and hydraulic conductivities, an independent estimate of either parameter is required to obtain a potentially unique solution to the model. The estimated regional recharge rate was therefore considered fixed during the calibration, and only hydraulic conductivities varied. The original model was run with the initial conditions and the conductivities adjusted within sensible boundaries until a best fit between measured and computed heads, respectively, and the interpolated water table contours were achieved (Figure 3.13).

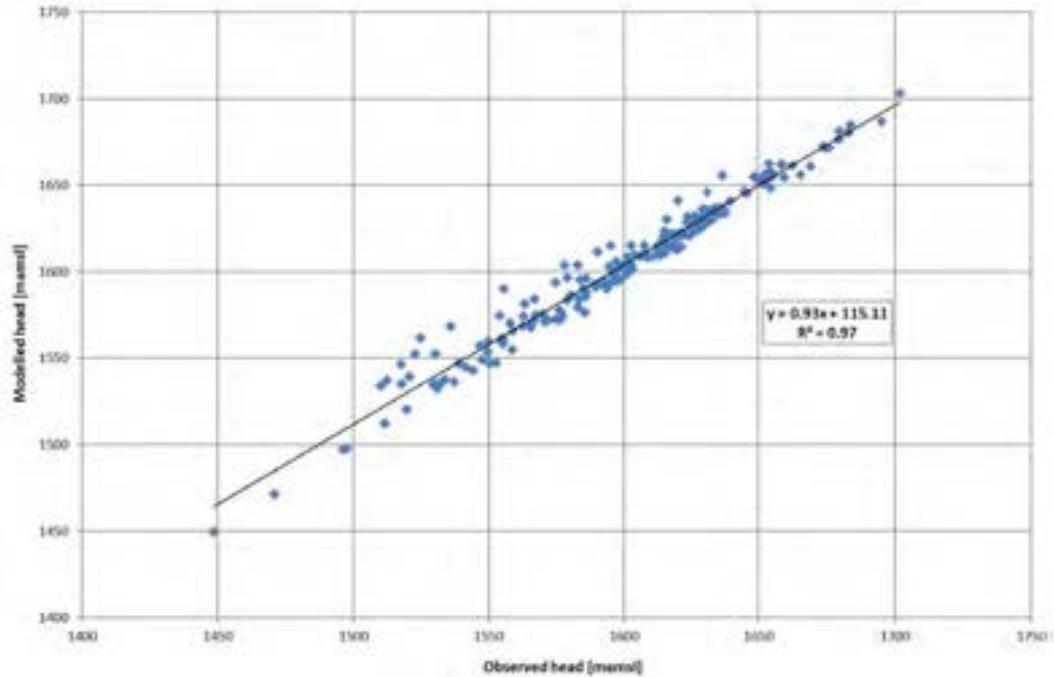


Figure 3.13: Steady-state calibration of the final Witwatersrand Goldfields Irrigation Groundwater Model

The root mean square error (RMSE) and the normalised root mean square error (NRMSE) were used as quantitative indicators for the adequacy of the fit between the 218 ($=n$) observed (h_{obs}) and simulated (h_{sim}) water levels:

$$RMSE = \sqrt{\frac{\sum(h_{obs} - h_{sim})^2}{n}} \quad \text{Equation 15}$$

$$NRMSE = \frac{RMSE}{h_{max} - h_{min}} \quad \text{Equation 16}$$

The normalised root mean square error scales the error value to the overall range of observed heads within a model domain (here $h_{max} - h_{min} = 1701.82 \text{ mamsl} - 1448.54 \text{ mamsl} = 253.28 \text{ m}$). NRMSE values lower than 10% are generally considered acceptable.

A very good correlation between observed and modelled water levels ($R^2 = 0.97$ or 97% correlation, Figure 3.13) was achieved for the steady-state calibration. The corresponding root mean square error (RMSE) of 8.71 and the normalised root mean square error (NRMSE) of 3.44% for the steady-state calibration of the groundwater flow model are more than satisfactory for the study. The calibrated hydraulic conductivity values are shown in Figure 3.14 to Figure 3.16, while the simulated heads to be used as starting heads for the predictive model scenarios are shown in Figure 3.17.

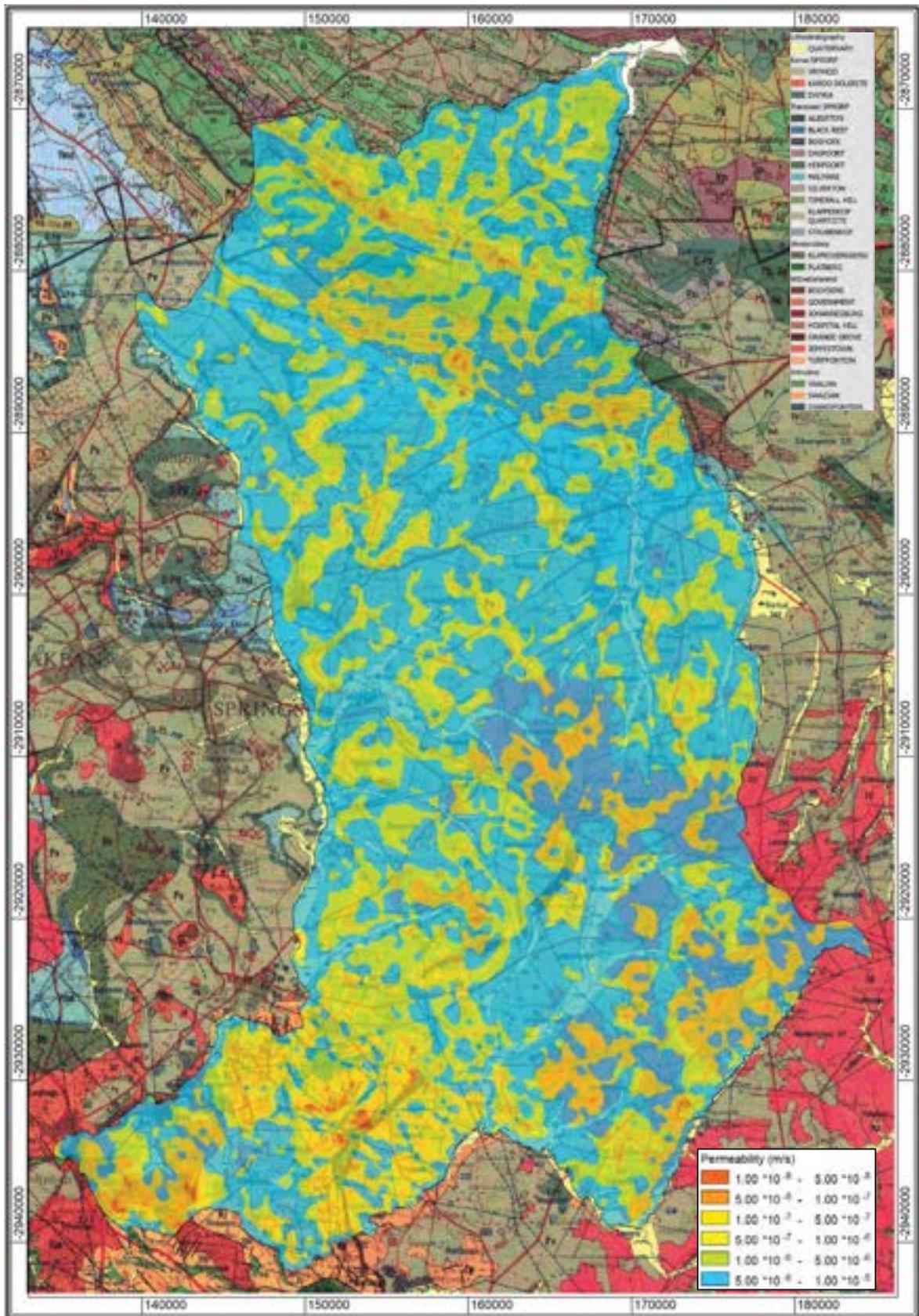


Figure 3.15 Calibrated hydraulic conductivities for the shallow weathered aquifer

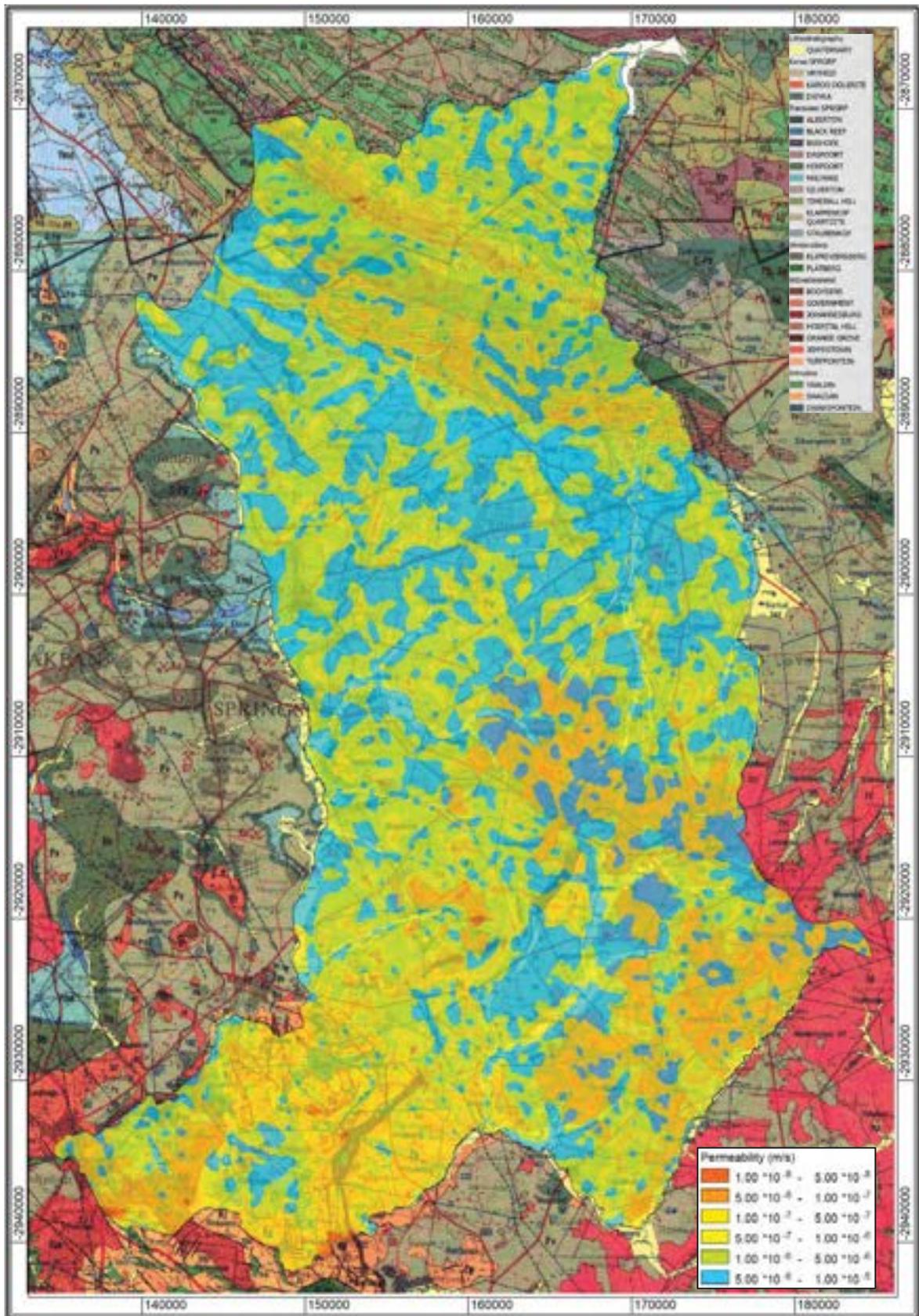


Figure 3.16 Calibrated hydraulic conductivities for the upper fractured aquifer

3.3 PREDICTIVE SIMULATIONS

3.3.1 Scenario overview

Following the model calibration, the project team recommended several modelling scenarios, generally related to the total area that can be irrigated with the current volumes of water being treated (110 Megalitres/day). The scenarios for total irrigation areas of 6000 ha and 2400ha were determined as follows:

- Scenario 1: The area required to fully utilise the available water (110 ML/day) is calculated based on the season where the least amount of irrigation is needed, which is summer, since rainfall supplies a large part of crop water requirements. In this scenario, a large area will be planted in summer (6000 ha), and a smaller portion in winter (2400 ha), because crop water requirements are higher in the dry season and there is insufficient water to irrigate the full 6000 ha. This means that 3600 ha of the total irrigated area would receive irrigation only in summer, and 2400 ha would receive irrigation in both summer and winter.
- Scenario 2: The area required to fully utilise the available water (110 ML/day) is calculated based on the season where the most irrigation to meet crop demand is needed, which is winter. In this scenario, the area that will be planted in summer will be less than the area required to utilise the available water, which means there will be excess water in the system in summer, and only 2400 ha will be irrigated in both summer and winter.

In addition to the scenarios based on the total area that can be irrigated, scenarios were considered based on the potential spatial spread of the irrigation pivots (concentrated vs dispersed), with concentrated irrigated areas expected to have a greater environmental footprint than the dispersed “irrigation mosaics” scenario:

- Total irrigated area of 2 400 ha with concentrated or dispersed pivots
- Total irrigated area of 6 000 ha in summer, which is fixed, with 2400 ha of summer-winter pivots that are either concentrated or dispersed

While irrigation pivots cluster and often neighbour each other in the concentrated scenarios, they are generally set apart in the dispersed scenarios.

3.3.2 Source term assumptions

To simulate the impact of mine water irrigation on the underlying aquifer, the return flows and concentrations reporting to the aquifer had to be estimated. The project team used the Irrigation Water Quality (IrrigWQ) decision support system developed by du Plessis, et al. (2023) to determine the fitness for irrigation of the mine waters, simulate the irrigation return flows (depending on the cropping system, i.e., summer and/or winter crops), and determine concentrations of major constituents of concern over a 45-year irrigation period. Estimates for the two irrigation areas (6000 ha and 2400 ha) are based on overhead irrigation systems or centre-pivot irrigation and assume a 1.2 m sandy loam profile. Irrigation of two different crops was simulated: maize for summer planting and oats for winter. Simulations were also performed for irrigation with untreated mine water and HDS-treated mine water.

The irrigation return-flows (Table 3.13) recharging the aquifer differed marginally for the 3600 ha of summer only irrigation (296 mm/a) and the 2 400 ha of summer and winter irrigation (293 mm/a) due to limited return flows in the winter months. However, the total leached salt concentrations for the double-cropping irrigation areas are expected to be double those of the summer-only irrigation areas, regardless of whether untreated or HDS-treated mine water is used for irrigation (Table 3.13). While the calcium concentrations in the return flows of the summer and winter areas were only around 10% higher than for the summer-only areas due to gypsum precipitation in the soil profile, sulphate concentrations were 90% higher (almost double) and magnesium, potassium, sodium, and chloride concentrations were around three times higher.

In other words, the return flow rates were, for all practical purposes, equal. However, the total salt mass flux in the summer- and winter-irrigation areas is twice that in the summer-only irrigation areas. Still, the composition changes due to gypsum precipitation, mainly in winter.

Table 3.13: Simulated irrigation return flows and concentrations

	Summer only Area		Summer-Winter Area	
Water balances				
Irrigation applied (mm/a)	223		668	
Rainfall (mm/a)	693		693	
Drainage (return flow) (mm/a)	296		293	
Leaching fraction (%)	32		22	
Irrigation Area (ha)	3 600		2 400	
Return Flow Concentrations (mg/L)				
	Untreated AMD	HDS Treated AMD	Untreated AMD	HDS Treated AMD
Calcium as Ca	307	301	338	342
Chloride as Cl	104	105	313	316
Potassium as K	12.3	12.3	36.9	36.9
Magnesium as Mg	106	90.6	319	273
Sodium as Na	174	177	525	533
Sulphate as SO₄	1 258	1 187	2 380	2 221
Salts, total	1961	1 872	3 913	3 723

3.3.3 Transport assumptions

It must be noted that the following model simulations assume no retardation due to, e.g. sorption, cation exchange, or any microbiological degradation in the subsurface. The simulated plumes, therefore, represent a conservative worst-case scenario for pollutant transport. In the absence of site-specific data, literature values of dispersivity were assigned to the aquifer: a uniform longitudinal dispersion length of 50 m and a transverse dispersion length of 10% thereof, or 5 m. No background concentrations were assumed in the model simulations to predict and visualise the net effect of the irrigation return flows on the ambient groundwater quality. The models were run with a weekly timestep over 50 years, and the simulated return flow concentration plumes were visualised.

A unit (100%) source concentration (return-flow concentration) and a recharge rate (return flow) of 293 mm/a was assumed for the summer and winter irrigation pivots. Since no element-specific retardation or transformation is simulated, the seepage plumes are visualised as percentages of the unit input/source concentration with a minimum increment of 10% up to 100%. The % concentrations were converted into element-specific concentrations using Table 3.13. The keys for converting relative plume concentrations to actual concentrations are presented in Table 3.14 and Table 3.15.

3.3.4 Simulation scope

The predictive simulations performed indicate the extent to which mine water constituents in the irrigation return flow will spread and migrate from the source. They also provide an indication of relative concentrations of the constituents in the plumes and the time it will take for these plumes to reach surface waters. However, these simulations do not quantify the impact because they do not account for the assimilative capacity of such water bodies, which will likely be significant. To conduct this environmental assessment, the flux emanating from the pivots, rather than just the concentration of constituents, is required, along with the flow rate or volume of the receiving water body, its background concentration, and the DWS-established Resource Quality Objective. Nonetheless, the simulations were an important first step in assessing the potential impact of large-scale mine-water irrigation in the Eastern Basin of the Witwatersrand.

Table 3.14 Key for converting relative plume concentrations (in %) to actual concentrations (in mg/L) for the summer-winter area

Map legend	Ca		K		Mg		Na		Cl		SO ₄	
	Untreated	HDS Treated	Untreated	HDS Treated								
10%	34	34	4	4	32	27	53	53	31	32	238	222
20%	68	68	7	7	64	55	105	107	63	63	476	444
30%	101	103	11	11	96	82	158	160	94	95	714	666
40%	135	137	15	15	128	109	210	213	125	126	952	888
50%	169	171	18	18	160	137	263	267	157	158	1 190	1 111
60%	203	205	22	22	191	164	315	320	188	190	1 428	1 333
70%	237	239	26	26	223	191	368	373	219	221	1 666	1 555
80%	270	274	30	30	255	218	420	426	250	253	1 904	1 777
90%	304	308	33	33	287	246	473	480	282	284	2 142	1 999
100%	338	342	36.9	36.9	319	273	525	533	313	316	2 380	2 221

Table 3.15 Key for converting relative plume concentrations (in %) to actual concentrations (in mg/L) for the summer-only area

Map legend	Ca		K		Mg		Na		Cl		SO ₄	
	Untreated	HDS Treated	Untreated	HDS Treated								
10%	31	30	1	1	11	9	17	18	10	11	126	119
20%	61	60	2	2	21	18	35	35	21	21	252	237
30%	92	90	4	4	32	27	52	53	31	32	377	356
40%	123	120	5	5	42	36	70	71	42	42	503	475
50%	154	151	6	6	53	45	87	89	52	53	629	594
60%	184	181	7	7	64	54	104	106	62	63	755	712
70%	215	211	9	9	74	63	122	124	73	74	881	831
80%	246	241	10	10	85	72	139	142	83	84	1006	950
90%	276	271	11	11	95	82	157	159	94	95	1132	1068
100%	307	301	12	12	106	91	174	177	104	105	1258	1187

3.3.5 2 400 ha double-cropping irrigation scenarios

These scenarios investigated the impact on the receiving aquifer of establishing 2 400 ha of summer and winter crops under irrigation, either dispersed or concentrated. While the logistics and costs of delivering irrigation water to concentrated irrigation pivots are obviously easier and lower than for the irrigation mosaics option, the concentrated return flows and mass fluxes are likely to trigger higher salt concentrations within the underlying aquifer, but over a smaller area.

Simulated irrigation return flow plumes are visualised from Figure 3.18 to Figure 3.23 and in Appendix A. The extent of the individual plumes is not clearly visible in these images. However, higher resolution maps are available digitally. Nonetheless, the most pertinent points of discussion of the very conservative (no retardation or transformation, i.e. worst case) seepage plumes are as follows:

- The irrigation return flow plumes for the dispersed and concentrated pivot scenario generally start reaching surface water courses after 10 years (Figure 3.18 and Figure 3.19).
- With continuous irrigation return flows and conservatively assumed no retardation within the aquifer, the concentrations reporting as groundwater baseflow to the surface water drainage network increase over time. After 50 years of irrigation, return flow plumes reporting surface water drainage networks reached up to 80% of the source concentration for pivots close to water courses, for both the dispersed and concentrated area scenarios (Figure 3.22 and Figure 3.23), albeit more frequently for the concentrated area scenario.
- After 25 years of irrigation, 20% of the pivot return flow plumes are expected to reach surface water courses (Figure 3.20 and Figure 3.21), this figure increases to 40% after 50 years (Figure 3.22 and Figure 3.23).
- The return flow plumes of the concentrated pivot scenario extended further than those of the dispersed pivots and reached higher concentrations as a result of overlapping with neighbouring plumes and locally enhanced recharge rates.

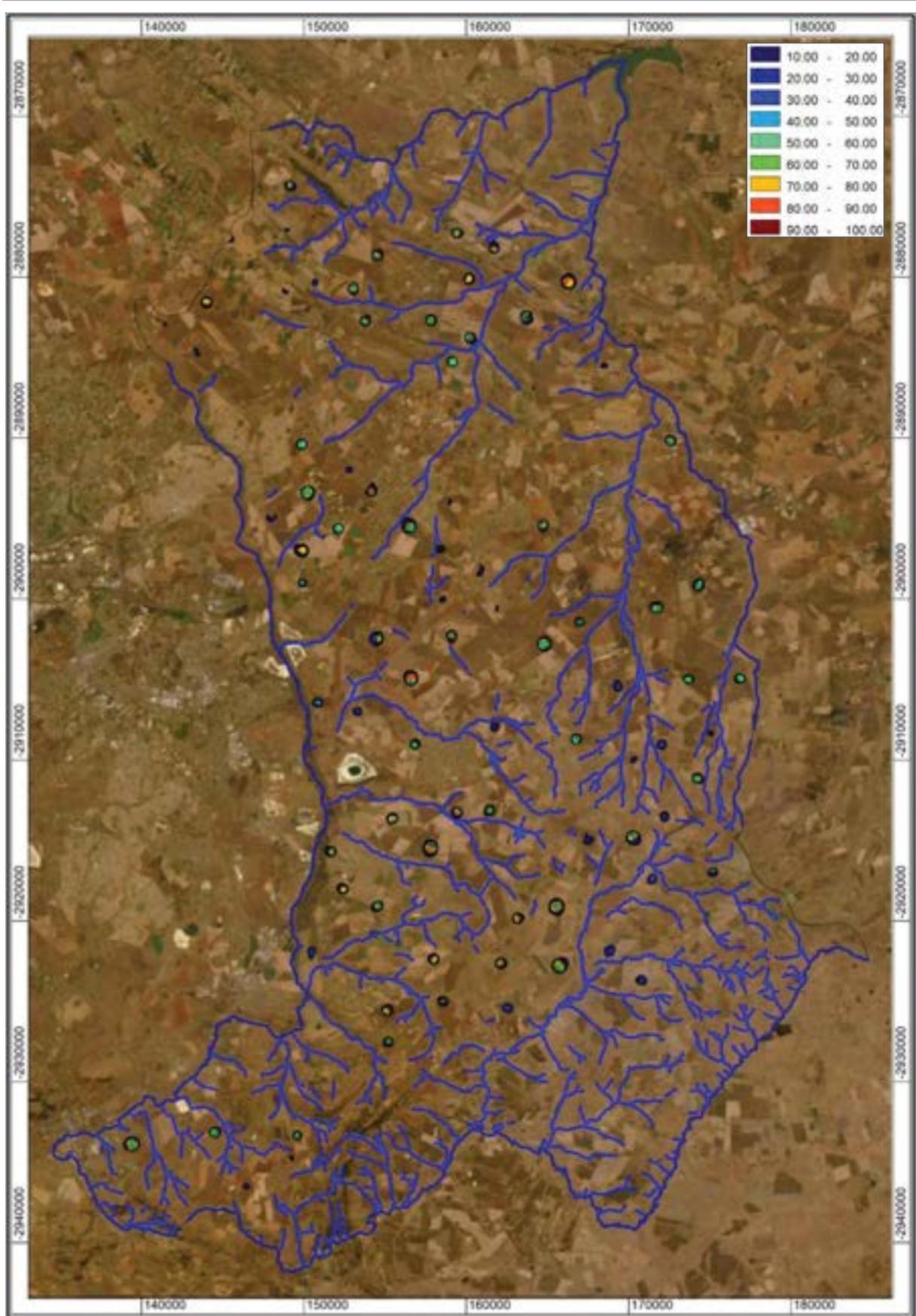


Figure 3.18. Irrigation Return Flow Plumes after 10 years for the 2 400 ha Scenario with Dispersed Irrigation Pivots

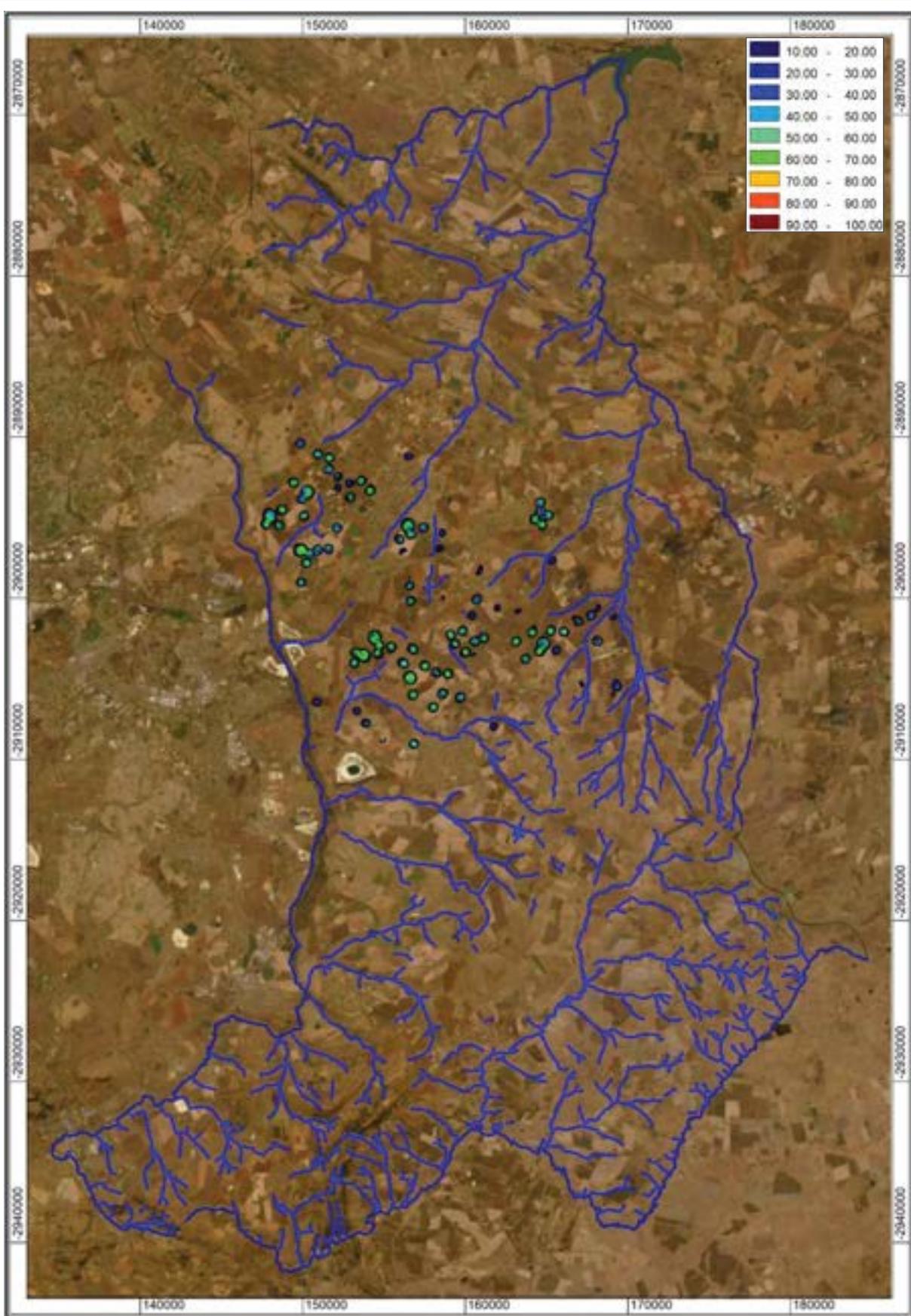


Figure 3.19 Irrigation Return Flow Plumes after 10 years for the 2 400 ha Scenario with Concentrated Irrigation Pivots

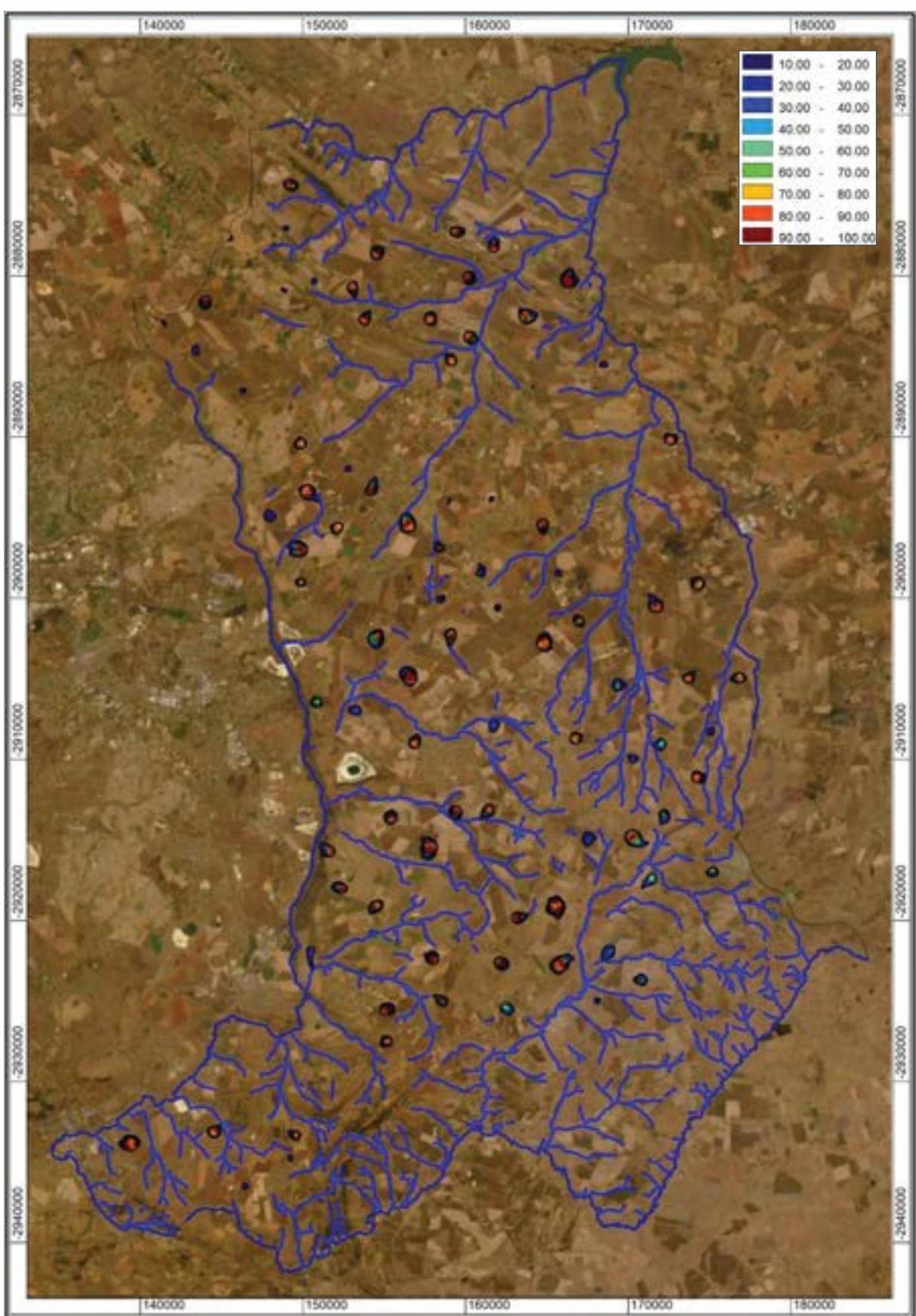


Figure 3.20 Irrigation Return Flow Plumes after 25 years for the 2 400 ha Scenario with Dispersed Irrigation Pivots

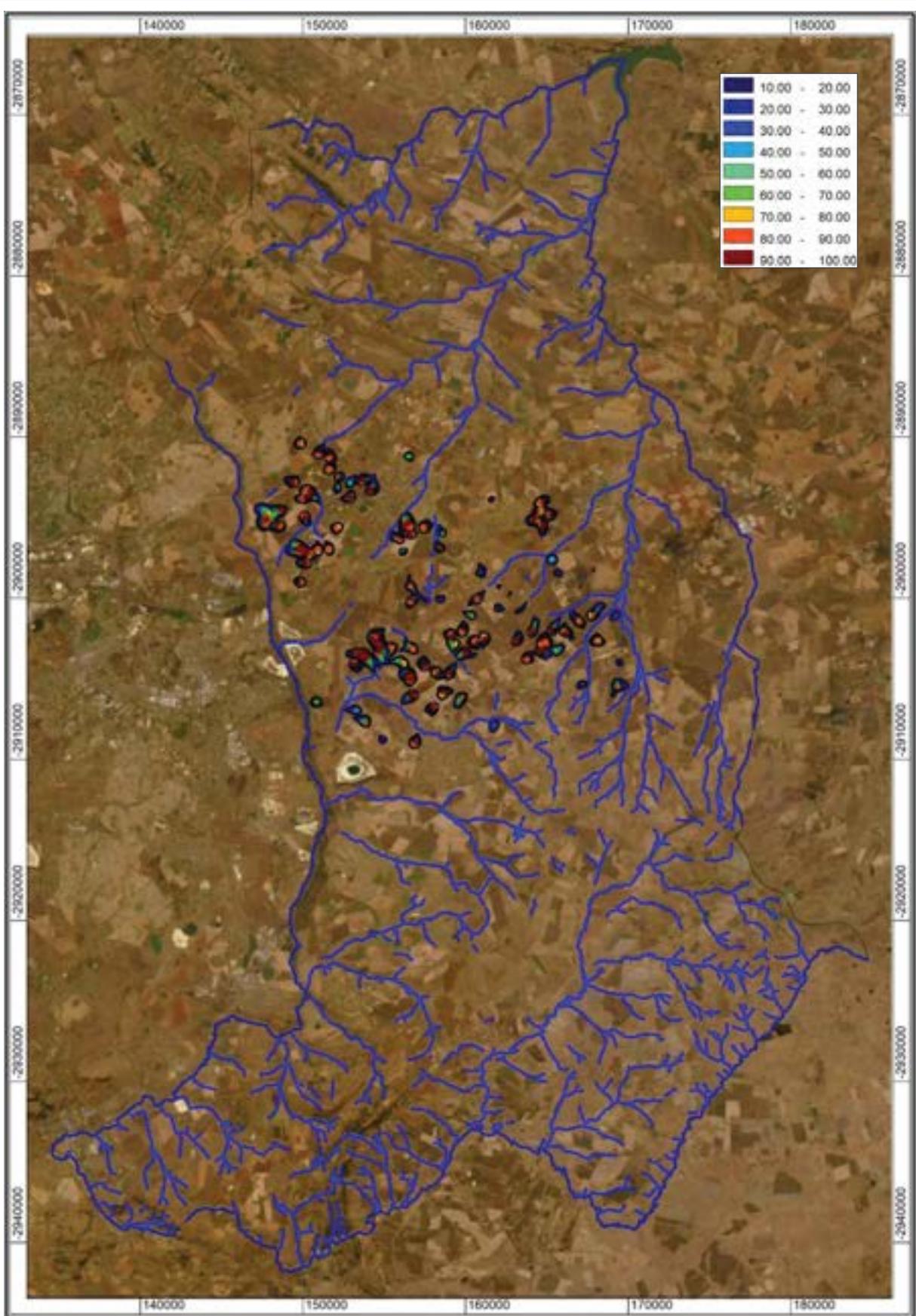


Figure 3.21 Irrigation Return Flow Plumes after 25 years for the 2 400 ha Scenario with Concentrated Irrigation Pivots

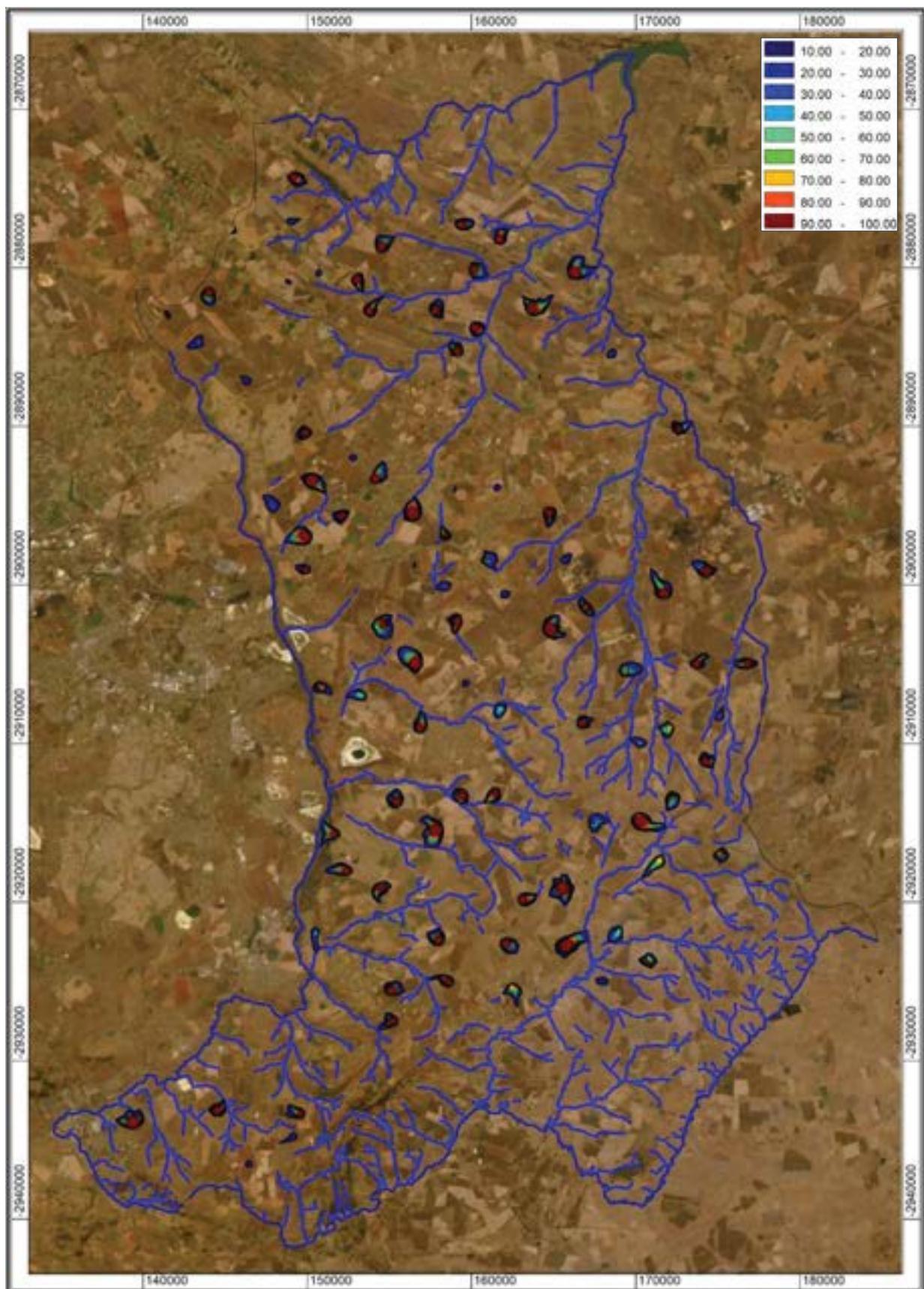


Figure 3.22: Irrigation Return Flow Plumes after 50 years for the 2 400 ha Scenario with Dispersed Irrigation Pivots

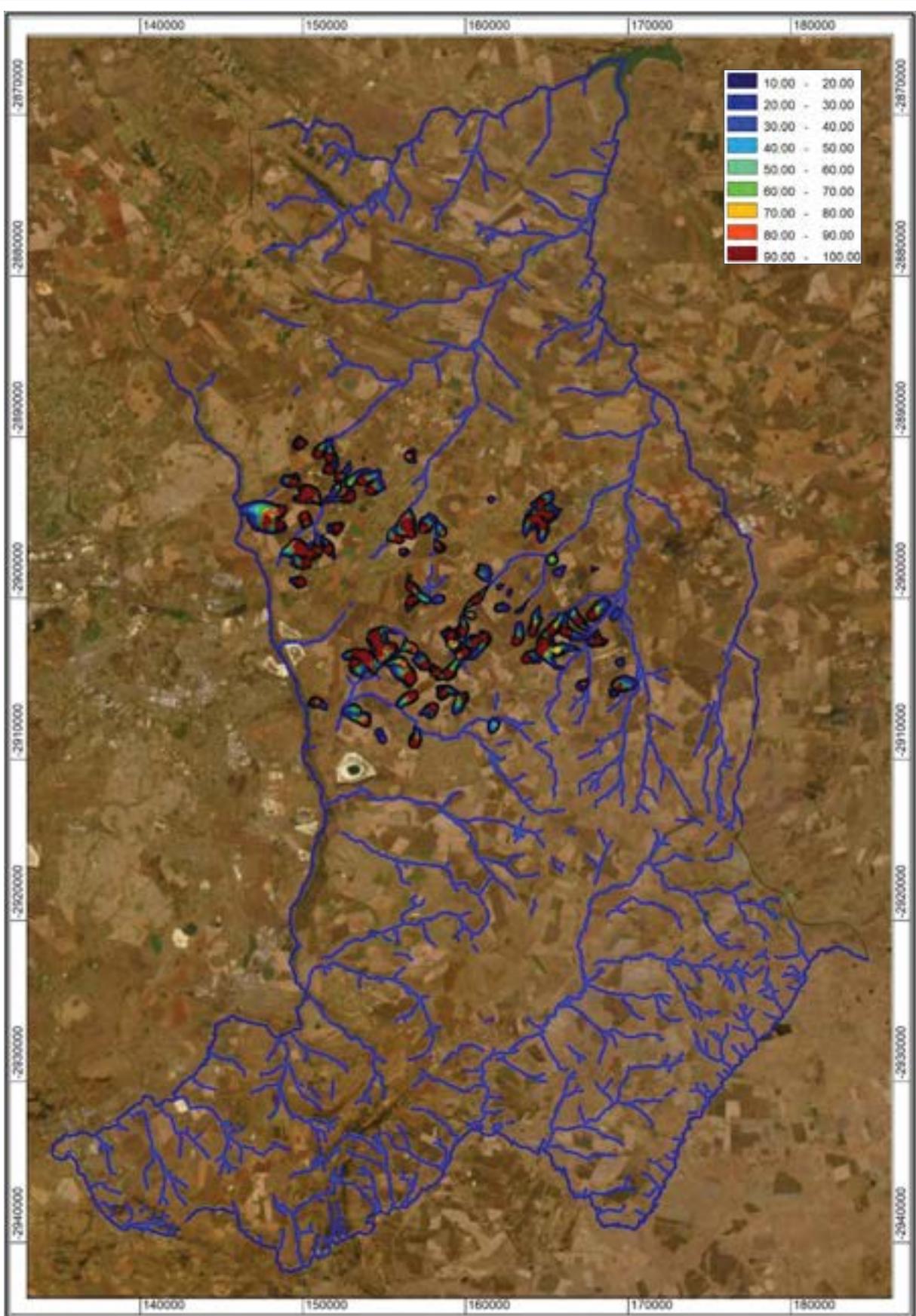


Figure 3.23: Irrigation Return Flow Plumes after 50 years for the 2 400 ha Scenario with Concentrated Irrigation Pivots

3.3.6 6 000 ha irrigation scenarios

The 6 000 ha scenarios assume that a combined 3 600 ha is irrigated only in summer, with a return flow rate of 296 mm/a, while a combined 2 400 ha is planted and irrigated in summer and winter, with a return flow rate of 293 mm/a. As before, a concentrated and dispersed pivot scenario for the double-cropped area (2 400 ha) is simulated. While the assignment of slightly different recharge rates is straightforward, the source concentration of the return flows for the summer and winter versus the summer-only cropped areas (Table 3.13) is less trivial, as discussed in Section 3.3.2.

To prevent repetition of the maps for each constituent, two sub-scenarios were simulated:

- A 2:1 scenario, where the source concentration of the double-cropped areas (100%) is twice as high as for the summer-only irrigated areas (50%), regardless of untreated or HDS-treated mine water. This scenario is applicable for the total leached salt concentrations and for all practical purposes, sulphate (1.9:1, Table 3.13).
- A 3:1 scenario where the source concentration of the double-cropped areas (100%) is three times higher than the summer-only irrigated areas (33%), regardless of untreated or HDS-treated mine water. This scenario applies to sodium, chloride, potassium, and magnesium.
- The conversion from relative % to actual concentrations of the assessed constituents is given in Table 3.14
- No separate scenario was simulated for calcium, as the slightly increased calcium concentration of the summer and winter plant areas (+10%) is well within the model accuracy (source term and transport model) and therefore essentially covered in the 2 400 ha scenario.

3.3.6.1 Presentations of the Model Results for the 6 000 ha Scenario based on expected source concentrations

Simulated irrigation return flow plumes for the 2:1 scenario are visualised in Figure 3.24 to Figure 3.27 and the 3:1 scenario (dispersed irrigation pivots only) is presented in Figure 3.28 to Figure 3.30. As before, the scale of the maps prohibits the determination of the extent of the individual plumes. The most pertinent points of discussion about the 6 000 ha scenario, in addition to the earlier points, are as follows:

- The irrigation return flow plume concentrations are expected to be higher for the double-cropping irrigation area than for the summer-only irrigation areas due to their higher return flow concentrations. This is even more pronounced in the 3:1 scenario (sodium, chloride, potassium, and magnesium).
- A few irrigation return flow plumes (3%) reach surface water courses within ten years, more within 25 years (20%) and most after 50 years (up to 47%). Irrigation with mine water is expected to impact the underlying and downstream aquifer, as well as surface water courses.

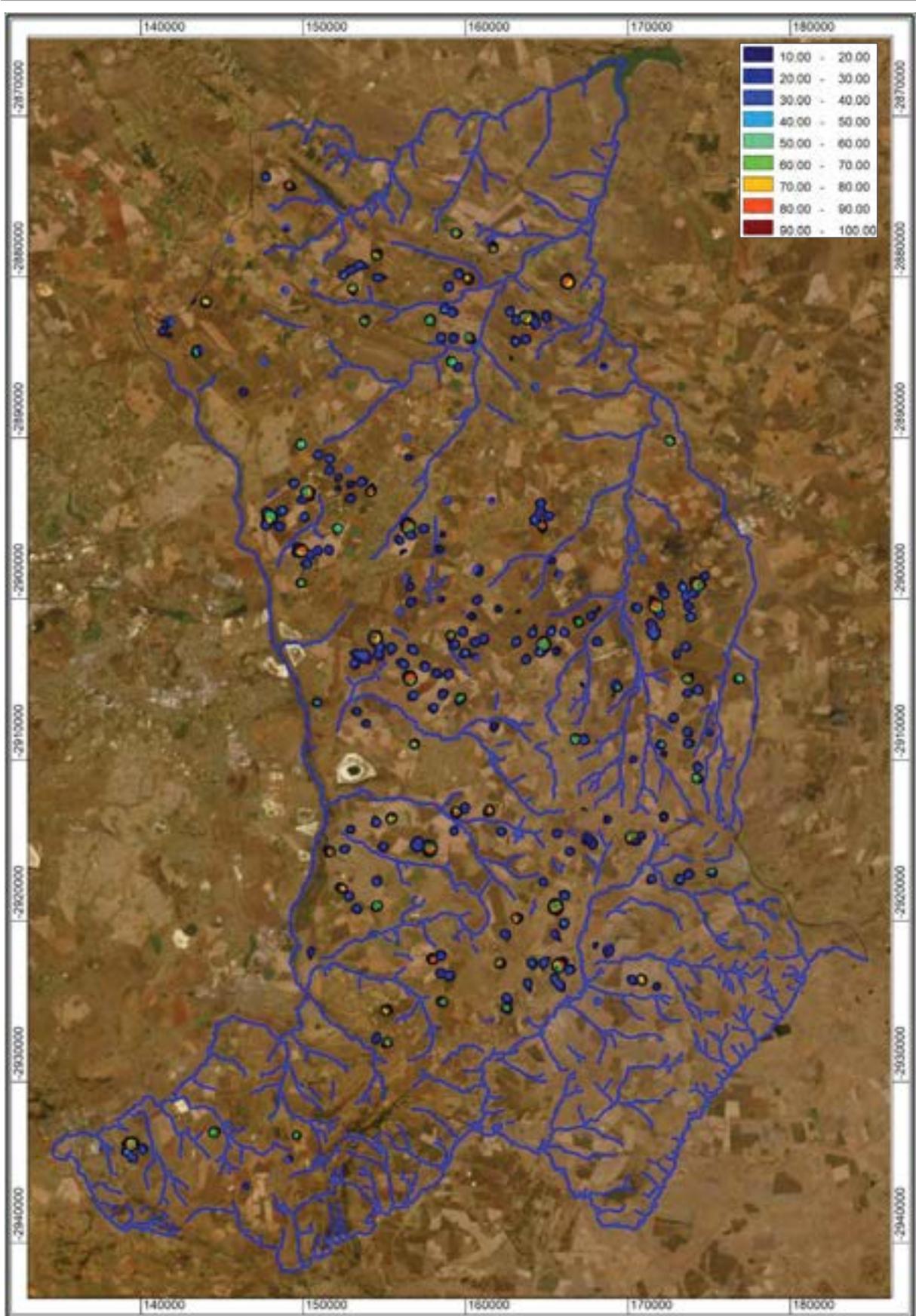


Figure 3.24: Irrigation Return Flow Plumes after 10 years for the 6 000 ha Scenario with Dispersed Irrigation Pivots

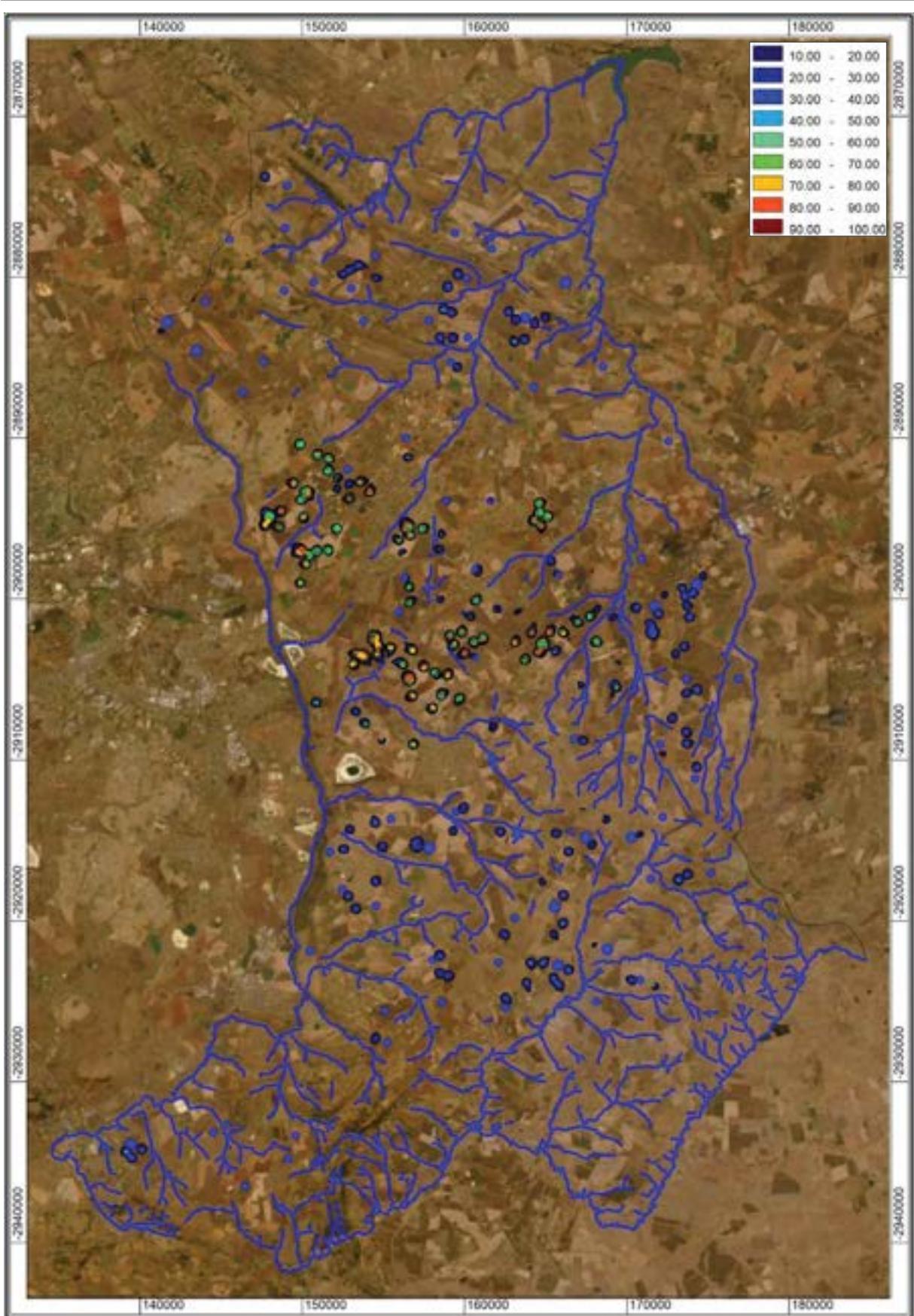


Figure 3.25 Irrigation Return Flow Plumes after 10 years for the 6 000 ha Scenario with Concentrated Irrigation Pivots

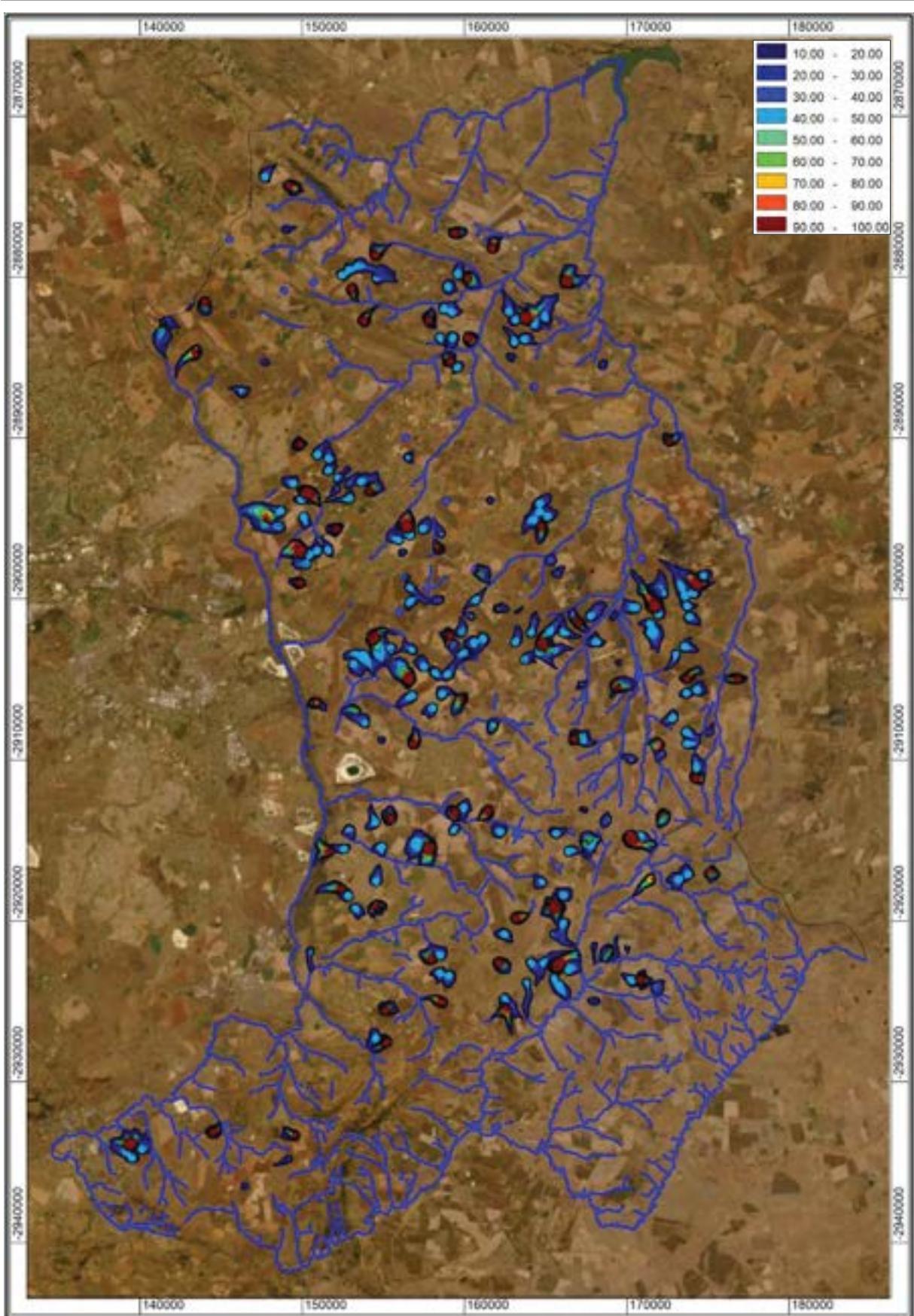


Figure 3.26: Irrigation Return Flow Plumes after 50 years for the 6 000 ha Scenario with Dispersed Irrigation Pivots

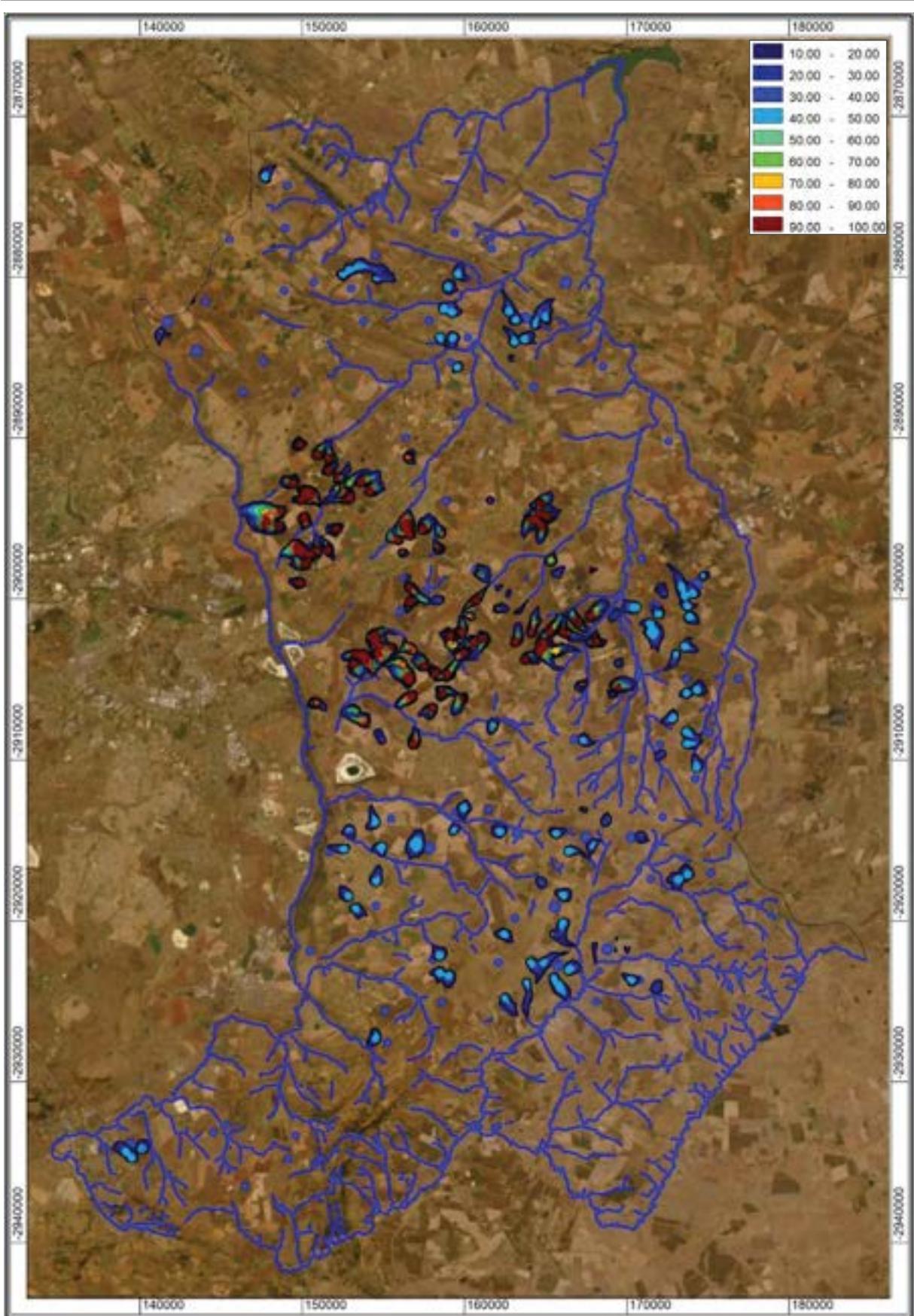


Figure 3.27 Irrigation Return Flow Plumes after 50 years for the 6 000 ha Scenario with Concentrated Irrigation Pivots

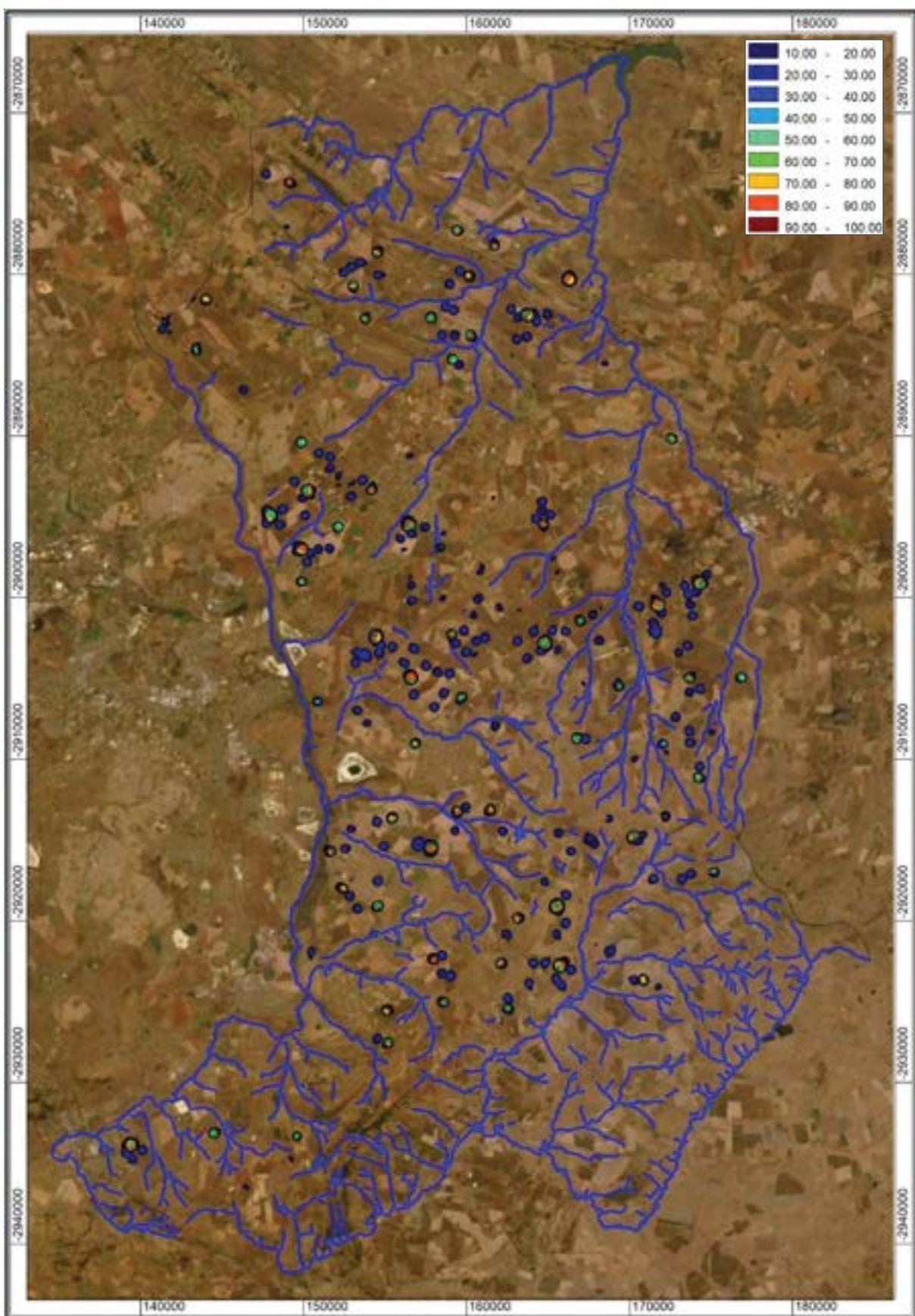


Figure 3.28: Irrigation Return Flow Plumes after 10 years for the 6 000 ha 3:1 Scenario with Dispersed Irrigation Pivots

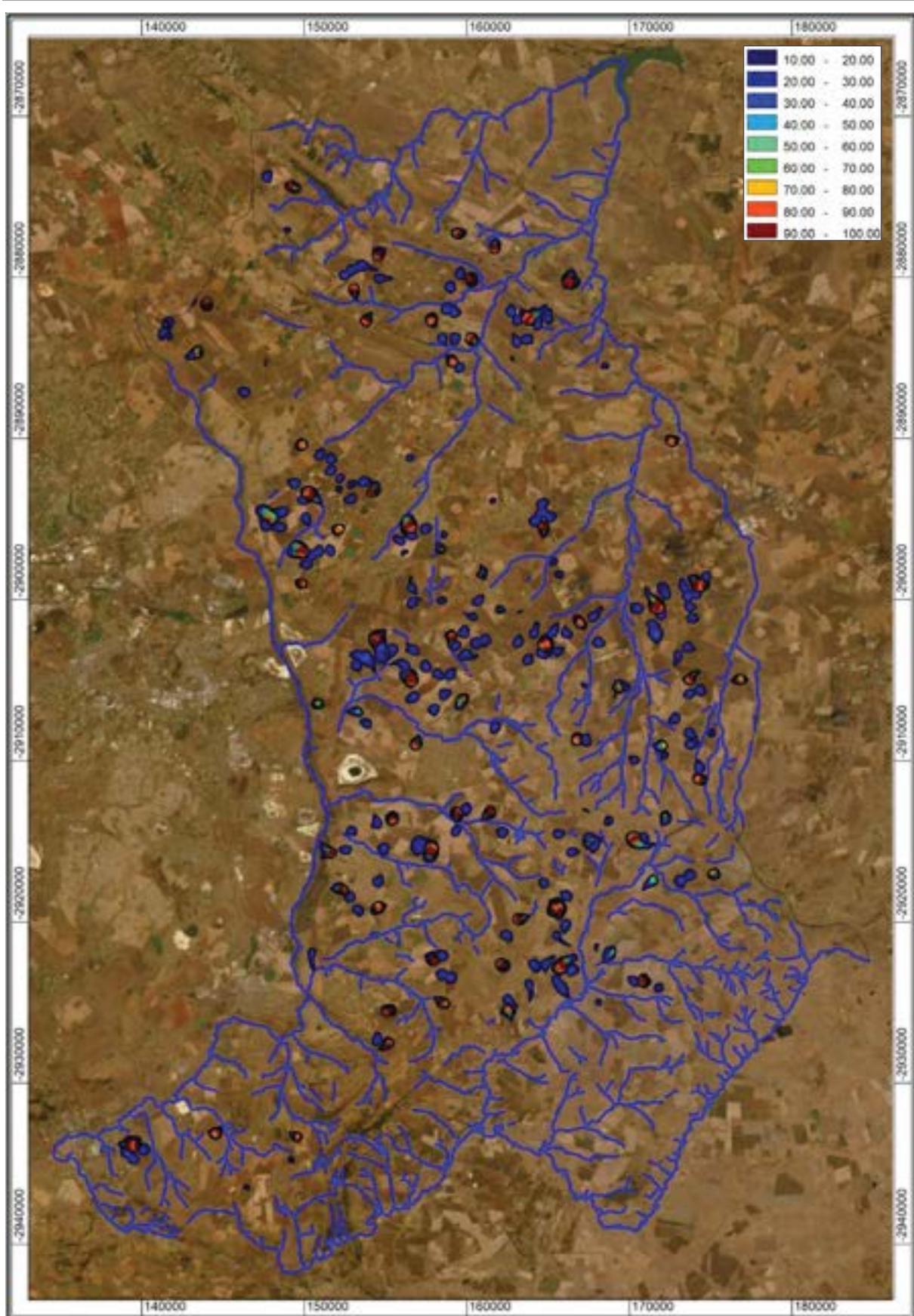


Figure 3.29: Irrigation Return Flow Plumes after 25 years for the 6 000 ha 3:1 Scenario with Dispersed Irrigation Pivots

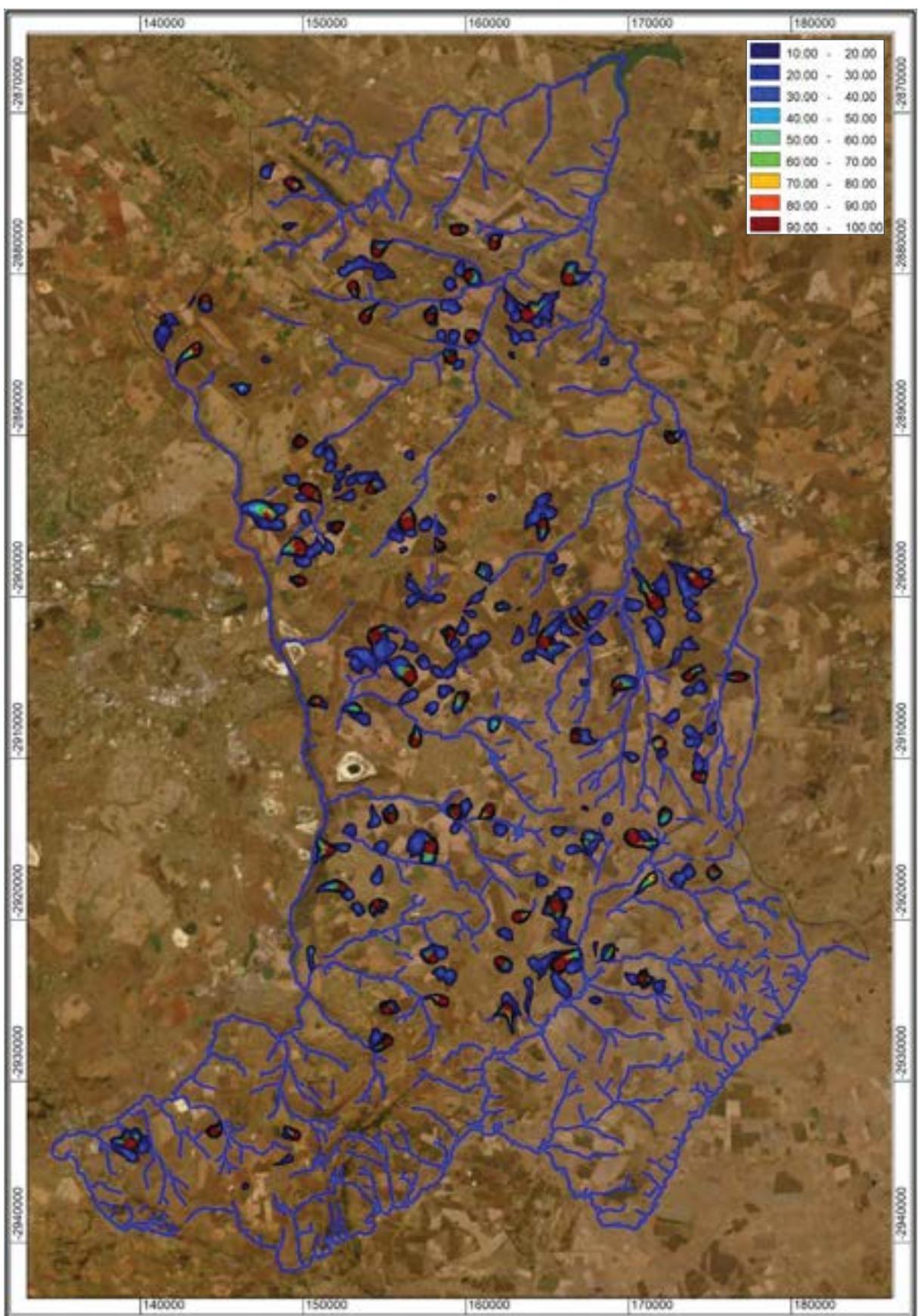


Figure 3.30: Irrigation Return Flow Plumes after 50 years for the 6 000 ha 3:1 Scenario with Dispersed Irrigation Pivots

3.3.6.2 Detailed Presentations of the Model Results for the 6 000 ha Scenario with dispersed pivots on the 2400 ha summer-winter area

Due to scale, the extent of the individual plumes is not clear on the maps presented. Therefore, two areas were selected (Figure 3.31) from the 6 000 ha dispersed irrigation scenario (3 600 ha of summer-only and 2 400 ha of dispersed double-cropping summer and winter irrigation areas) for detailed presentations and discussion of the irrigation return flow plumes (Figure 3.32 to Figure 3.37).

Observations made from the simulated irrigation return flow plumes for pivots located in the selected areas are as follows:

- With the irrigation pivots being further away from surface water courses (Area 1), the plumes reached these only after 15 years, with 10-20% of source concentrations (Figure 3.34). The concentrations reporting to the surface water drainage features increased after 50 years, to 50-60% of source concentrations.
- The irrigation return flow plume from one summer and winter plant area in Area 2 reaches the surface water course after 10 years, with 10-20% of the source concentrations increasing after 50 years to 80-90% of the source concentrations (Figure 3.32).
- The irrigation return flow plume from one of the summer pivots in area 2 reached the surface water course after 15 years with 10-20% of the source concentration (Figure 3.35), increasing to 30-40% after 50 years (Figure 3.37).

3.3.7 Potential effects of irrigation on groundwater levels

Due to increased irrigation return flows (from 293 to 296 mm/a) compared to the natural recharge rate (~33 mm/a), the water tables beneath the irrigation pivots are expected to rise. The extent to which water tables will mound and potentially even rise to the surface depends on the vertical and horizontal hydraulic conductivities of the soil and the underlying aquifer at a specific site. The mounding water tables are also a primary driver of the spread of constituents of potential concern at a given site. To provide examples of the possible rise at a given site, the mounding of the water tables relative to natural recharge at the two detailed sites is shown in Figure 3.38 and Figure 3.39. The modelling outputs show that the steady-state or long-term mounding of the water table might reach up to 10 metres below ground level (in the examples below, up to 7 metres) and potentially might impact plant growth by creating waterlogging conditions. The examples further show that mounding is highly dependent on the proximity of irrigation return flows (cumulative impact) and the hydraulic properties of the underlying aquifer. A reasonable estimate of these properties is therefore required for any given irrigation site.

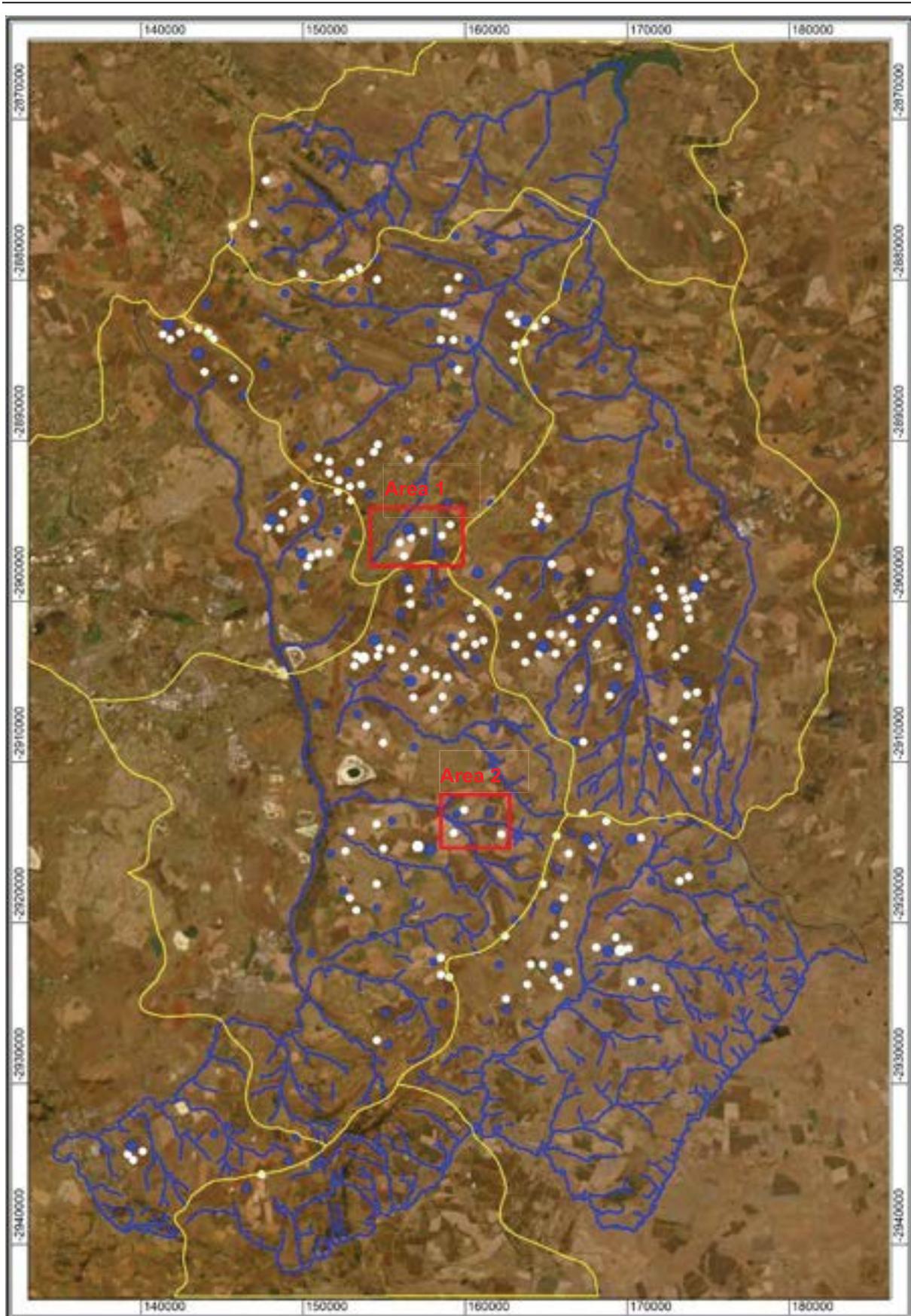


Figure 3.31. Location of the detail areas (summer irrigation area in white, summer and winter irrigation areas in blue)

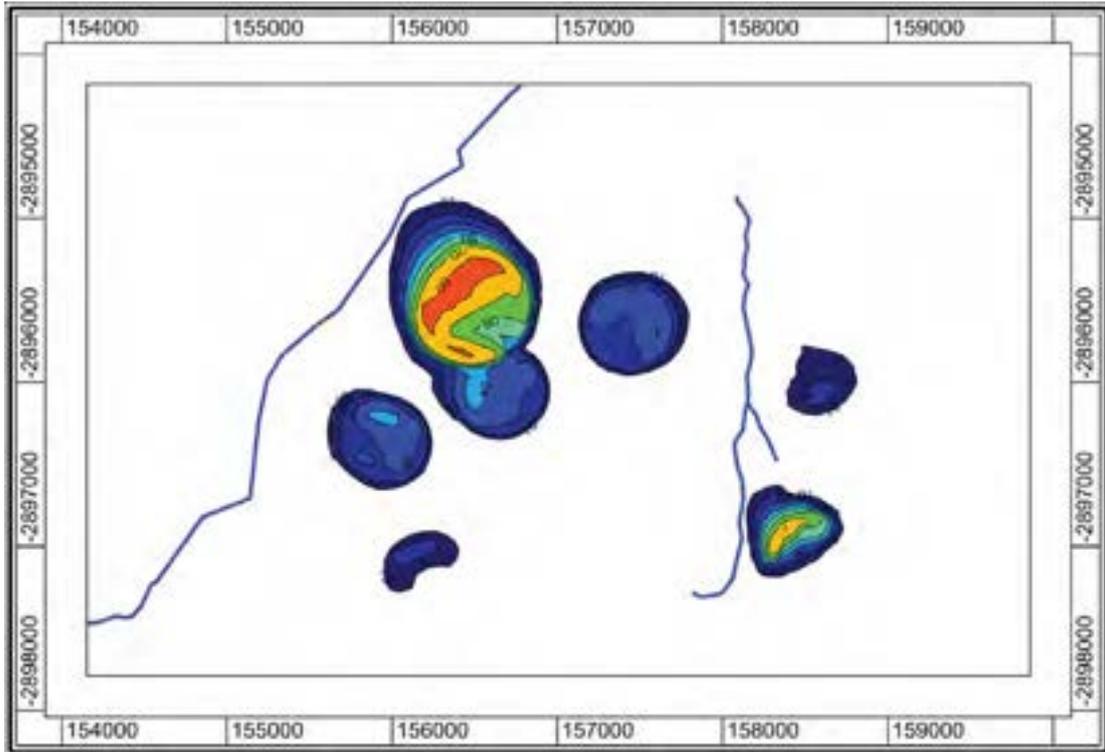


Figure 3.32: Irrigation Return Flow Plumes after 10 years (Area 1)

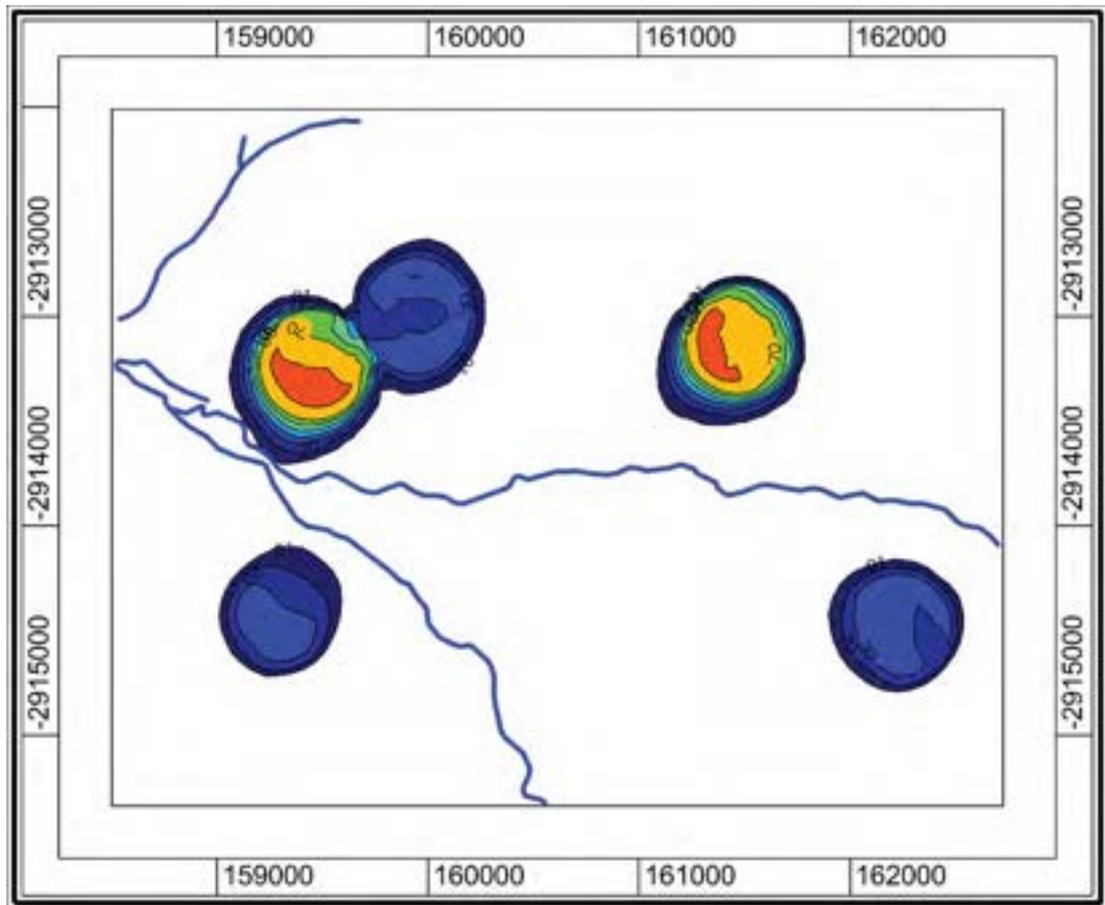


Figure 3.33: Irrigation Return Flow Plumes after 10 years (Area 2)

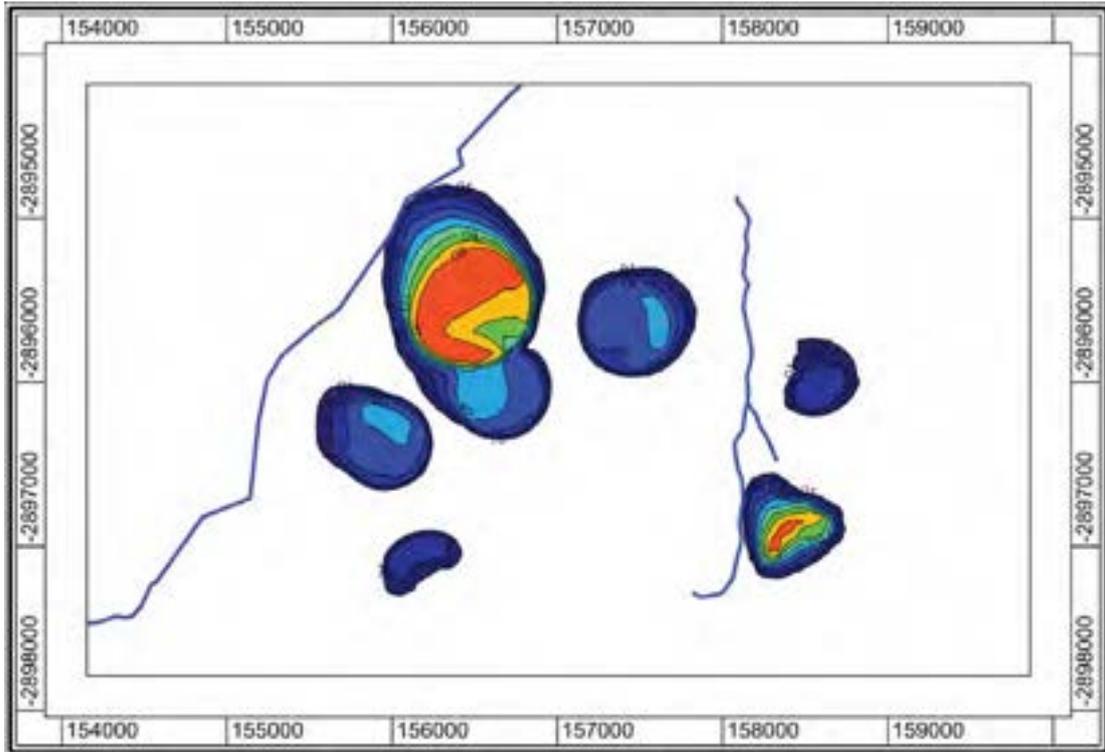


Figure 3.34 Irrigation Return Flow Plumes after 15 years (Area 1)

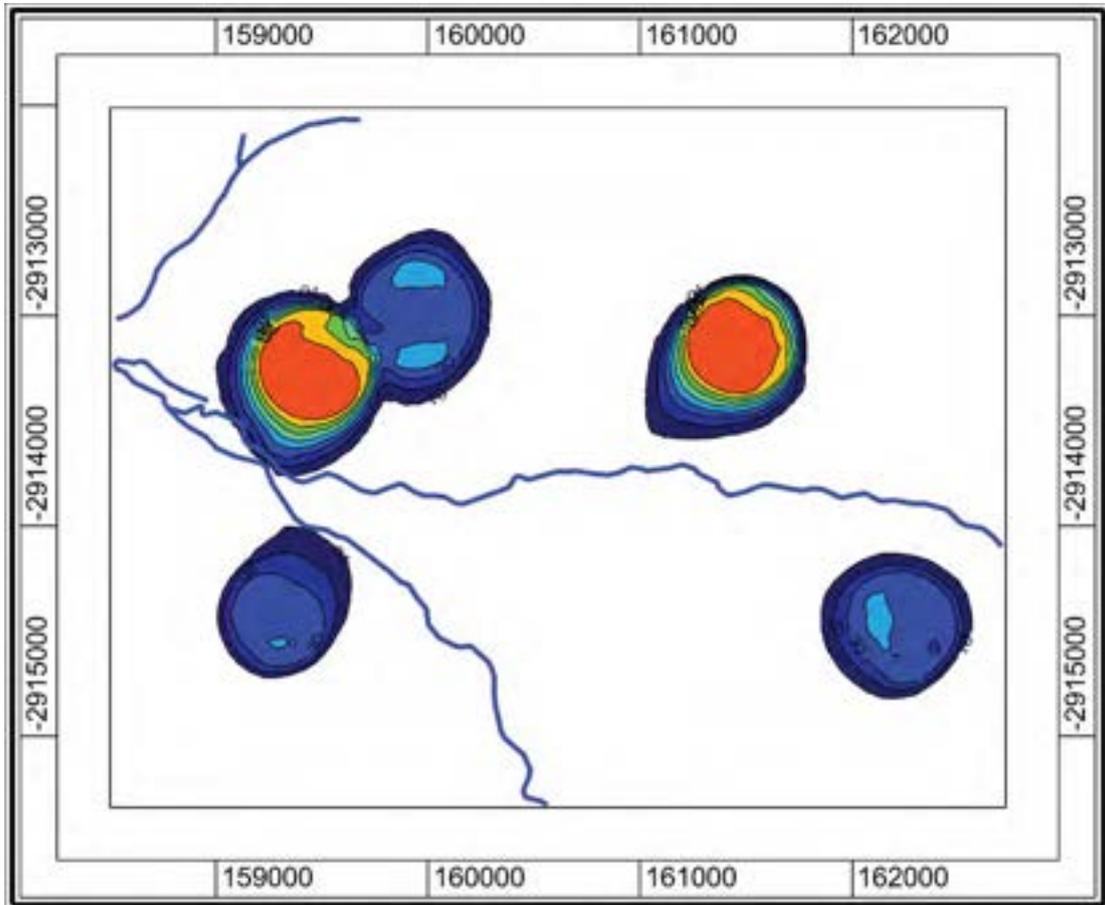


Figure 3.35: Irrigation Return Flow Plumes after 15 years (Area 2)

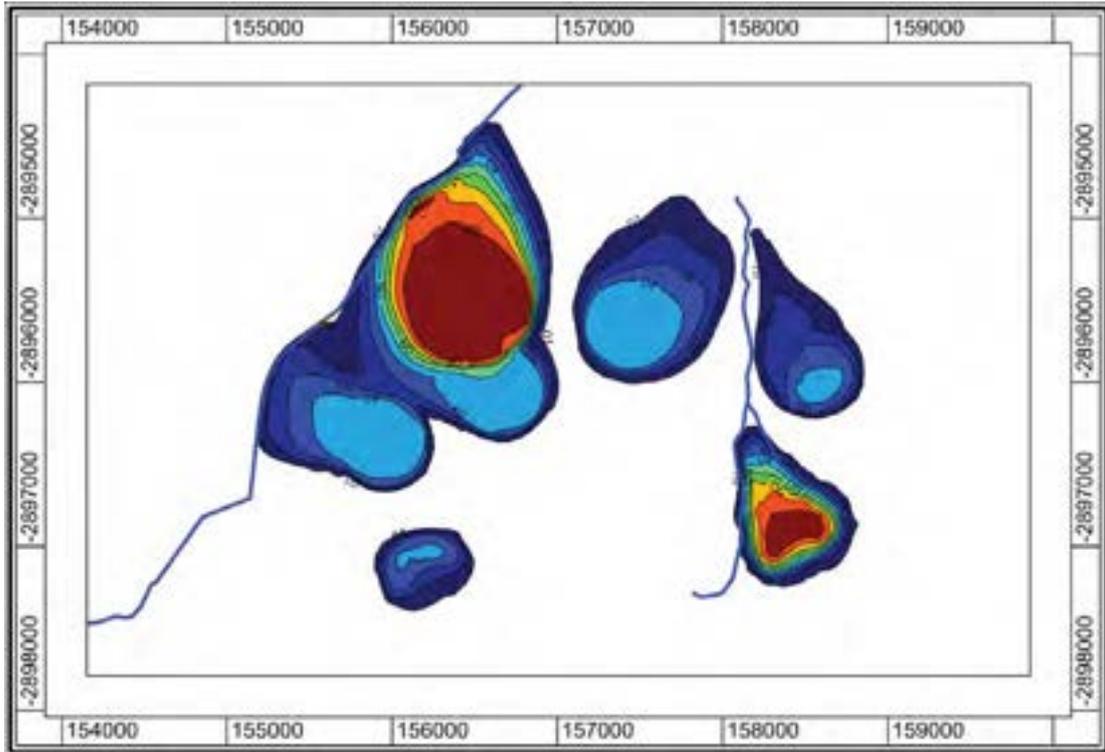


Figure 3.36: Irrigation Return Flow Plumes after 50 years (Area 1)

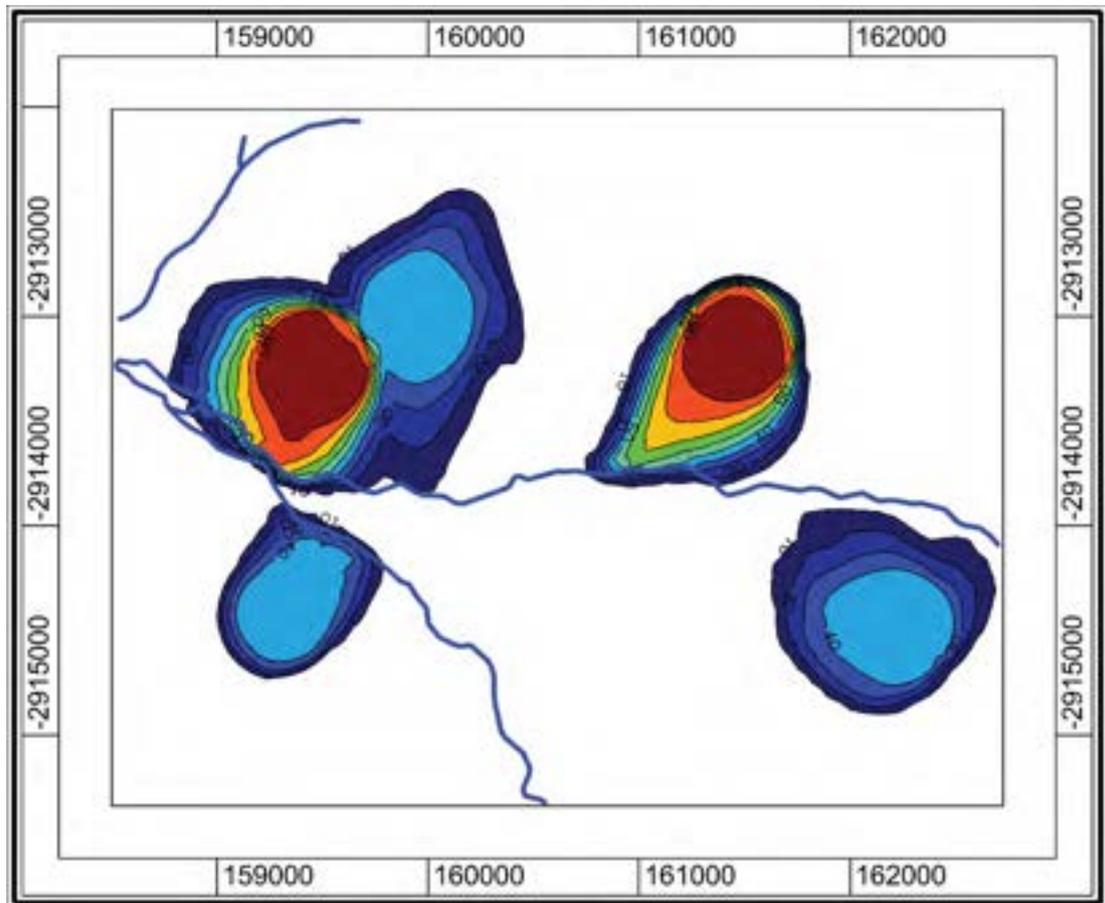


Figure 3.37: Irrigation Return Flow Plumes after 50 years (Area 2)

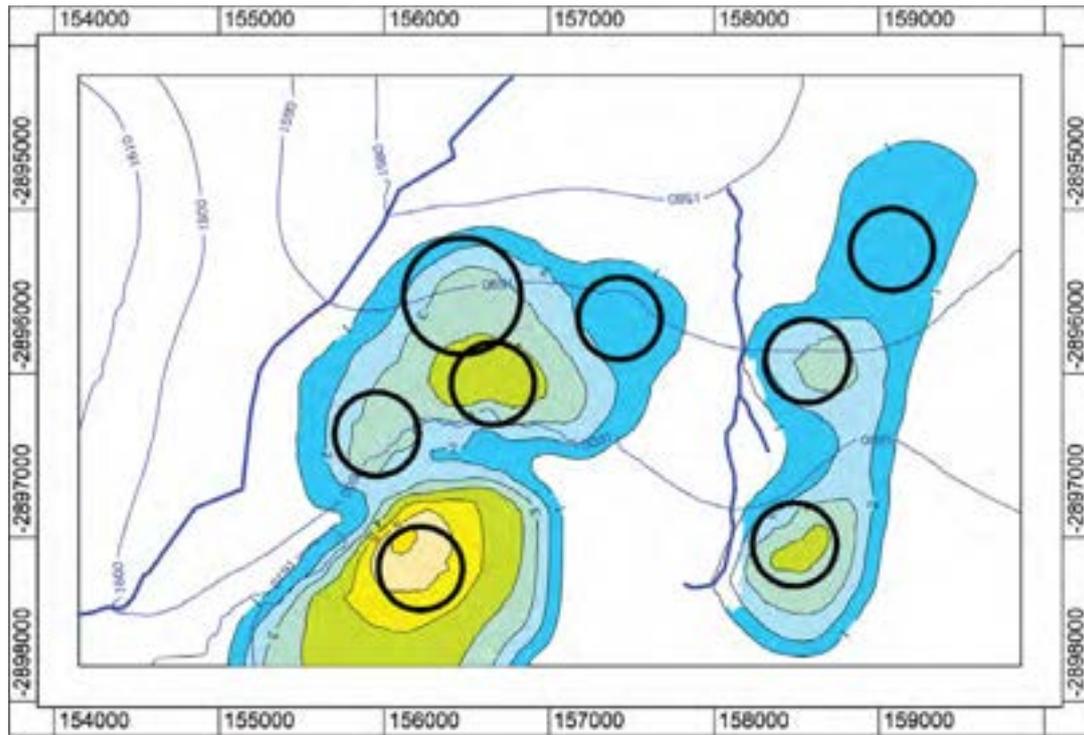


Figure 3.38: Mounding of the water table (contoured areas) due to irrigation return flows. Natural water table contour lines shown in blue (Area 1)

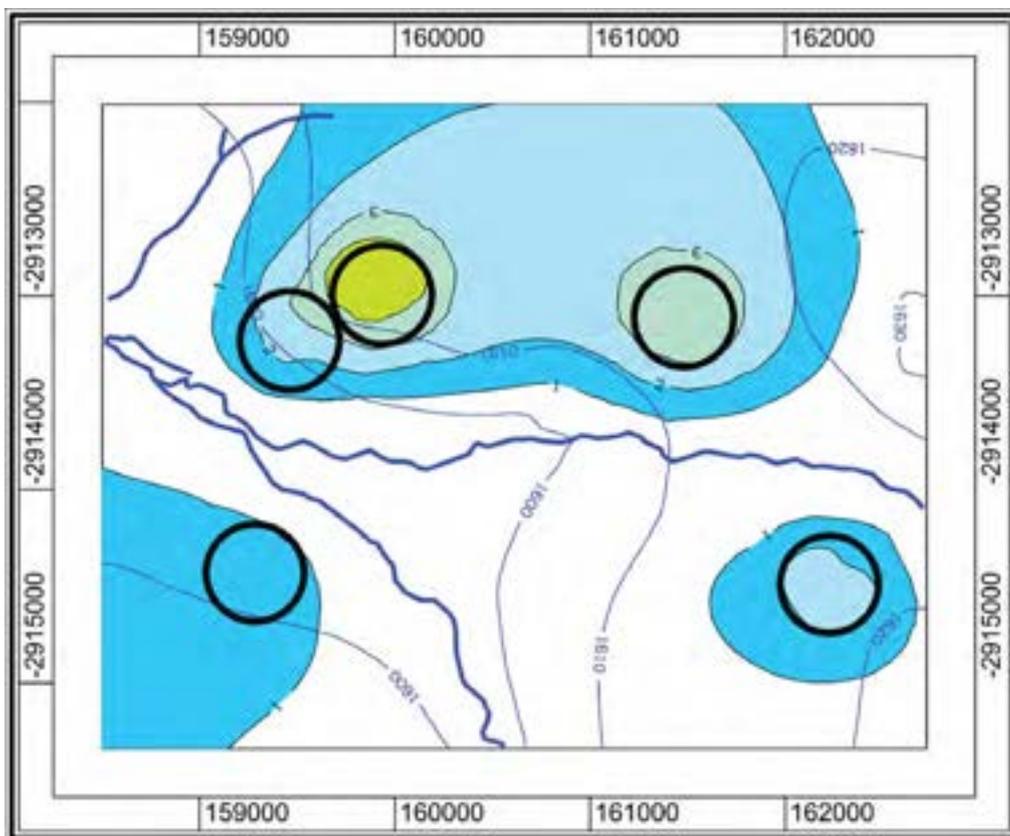


Figure 3.39: Mounding of the water table (contoured areas) due to irrigation return flows. Natural water table contour lines shown in blue (Area 2)

3.4 MONITORING REQUIREMENTS AND THRESHOLDS FOR ACTION

3.4.1 Key considerations

To irrigate agricultural land with mine water, a water-use licence must be obtained through the Department of Water and Sanitation's (DWS) water-use permitting system. This takes into account a detailed and individual assessment of on-site conditions, along with potential monitoring and mitigation measures. To assist with the assessment and planning of site-specific irrigation schemes, an Irrigation Water Quality Decision Support System (DSS) was developed locally by du Plessis et al. (2017), which can be used to model the effect of irrigation practices with specific mine waters under site-specific conditions. This model further indicates whether the proposed irrigation project would be sustainable in the long term and, if not, why, and contributes to a holistic, integrated decision-making process. Key considerations which are considered for irrigation with mine water include, but are not limited to:

- Aquifer classification: If irrigation is planned on a shallow sole-source aquifer, a critical site-specific investigation is required.
- Water quality: The irrigation water must be suitable for crop production. Irrigation water should be assessed in accordance with the South African Water Quality Guidelines, Agricultural Use: Irrigation (Department of Water Affairs and Forestry, 1996).
- The groundwater level should be considered based on the aquifer's parameters and classification.
- Community dependence on groundwater: If community dependence on groundwater is > 80%, irrigation with mine water should be considered only if the community is > 2 km away from the proposed irrigation site or upgradient, or if irrigation is planned for a very short period.
- Land stability: If the proposed irrigation site is in an area of land instability (where steep slopes cause run-off and soil erosion), in sinkhole areas or if there is an underlying dolomitic aquifer, irrigation with mine water should not be considered.
- If the proposed irrigation site is downgradient within 2 km of a nature reserve, wetland, Ramsar site, or a site of similar environmental importance, a site-specific environmental impact assessment is required by a specialist.

3.4.2 Monitoring requirements

Irrigation with mining-influenced waters will have some impact on water resources. However, this impact needs to be maintained at acceptable levels, and this can be achieved through monitoring and adaptive management. If a selected area meets all the required criteria for mine water irrigation outlined in the Technical Guidelines for Mine Water Irrigation, appropriate monitoring is essential (Heuer, et al., 2021). The monitoring programme must be site-specific and should consider regional biophysical (topography, land use, geology, ecosystems, and climate) and social factors (DWAF, 2006). Monitoring programs should protect water sources without overburdening irrigators. The recommended groundwater monitoring is as follows:

- A detailed conceptual model of the expected site hydrogeology should be constructed to identify priority areas for monitoring and guide the siting of monitoring boreholes. This should be accompanied by a comprehensive assessment of the geology and aquifer characteristics, followed up by model verification
- Depending on the site-specific irrigation water quality and geology, constituents of concern need to be identified
- At each pivot site or area with clusters of pivots, at least one down-gradient borehole should be installed. If adaptive management triggers are required at a site, it is suggested to construct a

borehole pair just outside the irrigated area, one into the weathered aquifer and one borehole into the hard rock below the weathered zone, downstream of the irrigated area.

- The borehole drilled into the weathered aquifer should have a very short length of solid casing, followed by slotted casing or a borehole screen to the bottom. If the material is not competent, it is recommended that a slotted piezometer with a gravel pack be installed to characterise shallow groundwater accurately.
- The borehole drilled into the hard rock below the weathered zone should be cased with solid casing that extends below the weathered zone
- Adequate sanitary seals and/or other preventative measures should be put in place to prevent the irrigation water from flowing directly into the boreholes.
- If an irrigation site is in proximity to a stream or river, and depending on the aquifer's hydraulic conductivity, it is suggested that an adaptive management trigger system be installed, comprising additional monitoring boreholes.
- Borehole construction must meet relevant regulatory requirements.
- The following parameters should be measured in each borehole:
 - **Water levels** every quarter
 - Groundwater sampling for the **macro-constituents** at least every **6 months**. The analytical constituents should include pH, EC, Ca, Mg, Na, K, SO₄, HCO₃, Cl, NO₃, PO₄, and any additional site- or mine-water-quality-specific constituents of concern.
- Implementation of monitoring:
 - Samples and data should be collected according to a detailed procedure (develop appropriate sampling procedures for the constituents of interest, e.g. rinsing of sample bottles, cooling of samples, time frame within which samples need to be delivered to the laboratory).
 - Sampling and analysis should be adequately representative of the irrigation area, and, if feasible, sample replication is recommended for data quality assurance.
- Data management:
 - Data should be compiled into a database and handled in accordance with DWAF's Minimum Requirements (2005).
 - Determine a uniform reporting format and procedure.
- Audit of monitoring programme:
 - Conduct internal/external audits of monitoring systems
 - Review and revise the monitoring design

In addition to the groundwater monitoring, an appropriate surface monitoring site should be identified. Ideally, a surface monitoring site directly downstream of the irrigation area, and not impacted by other activities that could compromise ambient water quality, should be selected. However, this is not always feasible.

3.4.3 Thresholds for action

To enable the sustainable use and responsible management of surface- and groundwater resources, the DWS uses a catchment and resource-directed approach. DWS has generated classes and resource quality objectives (RQOs) for significant water resources (rivers, dams, estuaries, and groundwater) across several catchments in South Africa. Integrated Units of Analysis (IUA) have been delineated within various Water Management Areas (WMA), which classify the extent of permissible utilisation and protection of water resources. RQOs have been defined for each IUA in terms of water quantity, quality, habitat and biota (Heuer et al., 2021). Water use licence quality threshold levels are set in accordance to the specific IUA Resource Quality Objectives.

On a site-specific basis, the potential effects of mine water irrigation on groundwater differ depending on the location of the irrigation site within South Africa, the proximity of the resource to the irrigated area, and the resource's position within the landscape (DWS, 2016). The natural physical and chemical characteristics and environmental roles of ground- and surface waters provide a baseline for setting site-specific thresholds within the IUA's RQO. Acceptable threshold values for the groundwater reserve within a catchment are usually based on the median value of each constituent plus 10% (DWS, 2018). However, the 75th percentile appears more reasonable given natural variations.

According to the RQOs for groundwater, long-term trends should not show negative quality deviations from natural levels. However, depending on the mine water quality used for irrigation and the irrigation period, large-scale mine water irrigation can influence the water quality of underlying aquifers (Heuer et al., 2021). To determine the thresholds for action to protect water resources in the vicinity of lands irrigated with mine waters, the following steps should be considered:

1. Identify and prioritise potential water resource(s) of concern;
2. Delineate the sphere of influence of irrigated land;
3. Quantify natural water resource(s) quality;
4. Define IUA and RQO water quality limits for irrigated site location (75th percentile of the data set), and
5. Negotiate a level of impact from mine water irrigation above the established RQO threshold levels. RQO threshold levels might have to be adjusted for site-specific compliance and defined based on distance from pivots to facilitate irrigation with mine water (if reasonable RQO levels are defined). (Similar to the concept of expected environmental concentrations in the old Waste Act.)

3.4.4 Site-specific example: Application of modelling results

In general, the quality of the Eastern Basin mine water is suitable for irrigation from a crop productivity perspective (Section 2.3). However, soil factors (e.g., soil depth, clay content, composition) at each irrigation site within the regional study area would need to be assessed to determine their suitability. From an ecological point of view, wetlands, which used to be part of a Ramsar classification, are located within certain irrigation areas, and site-specific investigations would be required per regulation by a wetland specialist.

Assuming the most conservative irrigation scenario utilising 6000 ha with dispersed summer and winter pivots (2400 ha), assuming no retardation, the irrigation return flow solute plume from a double-cropped irrigation pivot located in the Blesbokspruit catchment C21E reaches the surface water course after 10 years of irrigation (example area 2 in Figure 3.33). Source term concentrations of 10-20% can be expected in the irrigation return flow plume, which increase to 80-90% after 50 years of irrigation. An example of the irrigation plume concentrations compared with the groundwater reserve qualities, South African drinking water standards (SANS 241:2015), background qualities, quality of treated water

currently being discharged, and the surface water RQOs of the Blesbokspruit catchment C21E is provided in Table 3.16 and Table 3.17, respectively.

The Blesbokspruit quaternary catchment C21E is categorised as a water quality class 1, of which the predicted plume concentrations are within range and would not impact the water quality class during the first 10 years of irrigation, except 20% source term sulphate concentrations. Moreover, during the first 10 years of irrigation, most of the predicted concentrations for major groundwater constituents are within the range of the naturally observed groundwater quality at the various monitoring sites within the model area and do not exceed the SANS 241:2015 drinking water standard. Only the upper range of the predicted sulphate concentrations (20% source term concentration) generally exceeds the background sulphate concentrations observed in the groundwater (if not otherwise influenced by existing mine-impacted activities).

After 10 years of irrigation with the Eastern Basin mining-influenced waters, the estimated Mg, Na, and SO₄ concentrations in the irrigation return flow plume exceeded the groundwater quality reserve concentrations. In particular, sulphate concentrations are expected to exceed the groundwater reserve-quality limit by one order of magnitude, leading to long-term degradation of groundwater quality. Calcium and Cl concentrations also have the potential to exceed groundwater quality standards after more than 10 years of irrigation. It is important to note that the mean background groundwater quality already exceeds the groundwater quality reserves for all listed elements except potassium. This indicates that the RQOs are too conservative.

With regards to the surface water RQO of catchment C21E, all major constituents were well within the allowed threshold during the first 10 years of irrigation (Table 3.17) and well within the range of the observed surface water quality of the Blesbokspruit catchment. The 50-year irrigation scenario, however, indicated that Cl, Mg, Na, and SO₄ concentrations exceed both the RQO and SANS 2041:2015 drinking water standards and would negatively affect surface water quality if sufficient assimilative capacity is lacking. Again, it is important to note that background qualities and currently discharged treated water qualities also exceed these RQOs. The best way to determine if the impact is acceptable is to monitor surface water quality downstream of the irrigation development.

It is clear from these assessments that the current RQOs are too conservative and do not accommodate mine water irrigation. Given the potential benefits of using the Witwatersrand Goldfields mine waters for irrigation, a revision of the RQOs should be considered to facilitate this mine water management option.

Table 3.16 Modelled return flow plume concentrations after 10 years (10-20% of source term) and 50 years (80-90% of source term) of irrigation for the most conservative scenario compared to groundwater reserve qualities of catchment C21E

Irrigation water	Groundwater quality reserve	SANS 241:2015	Mean background quality	Untreated AMD Plume		HDS Treated AMD Plume	
% of source term concentration	C21E	Drinking water		10-20%	80-90%	10-20%	80-90%
Calcium as Ca	44	150	89	34-68	270-304	34-68	274-308
Chloride as Cl	32	300	193	31-63	250-282	32-63	253-284
Potassium as K	11	50	9	4-7	30-33	4-7	30-33
Magnesium as Mg	23	70	47	32-64	255-287	27-55	218-246
Sodium as Na	29	200	123	52-105	420-472	53-107	427-480
Sulphate as SO4	36	500	187	238-476	1904-2142	222-444	1777-1999
Salts, total				391-783	3130-3521	372-745	2978-3351

Table 3.17 Modelled return flow plume concentrations after 10 years (10-20% of source term) and 50 years (80-90% of source term) of irrigation for the most conservative scenario compared to surface water RQOs of catchment C21E

Irrigation water	Surface water RQO (unacceptable limit)	SANS 241:2015	Mean background quality	Discharged Treated AMD	Untreated AMD Plume		HDS Treated AMD Plume	
% of source term concentration	C21E	Drinking water			10-20%	80-90%	10-20%	80-90%
Calcium as Ca		150	175	249	34-68	270-304	34-68	274-308
Chloride as Cl	>200	300	212	84	31-63	250-282	32-63	253-284
Potassium as K		50	27	13	4-7	30-33	4-7	30-33
Magnesium as Mg	>70	70	82	97	32-64	255-287	27-55	218-246
Sodium as Na	>150	200	11	161	52-105	420-472	53-107	427-480
Sulphate as SO4	>500	500	80	950	238-476	1904-2142	222-444	1777-1999
Salts, total					391-783	3130-3521	372-745	2978-3351

3.5 CONCLUSION

A hydrogeological flow and transport model was developed to assess potential influences on the groundwater environment and on receiving surface water bodies (via base flow). Results from the various worst-case groundwater model scenarios suggest that large-scale mine water irrigation can be sustained in the medium- to long-term with minimal impacts on ground and surface water. Summer-only irrigation is expected to have fewer impacts than summer and winter irrigation. However, irrigating only in the summer will require managing excess water, which will have its own environmental implications.

Irrigation return flow plumes in a concentrated irrigation scenario, irrigated both during summer and winter, are expected to have a greater influence on the groundwater quality of the shallower weathered aquifer than dispersed irrigation pivots. Furthermore, the model predicted that elevated irrigation return flows (293 to 296 mm/a) compared to natural recharge rates (~ 33 mm/a) could cause mounding of the water table beneath the irrigation pivots. The results from the hydrogeological modelling highlighted the importance of the location and distribution of irrigated areas when considering mine water irrigation. The modelling results suggest that, for mine water irrigation to be sustainable, irrigated areas should ideally be located far from watercourses and spread across the landscape rather than concentrated in one area to minimise impacts.

It is important to note that the modelled scenarios indicate the time it will take for plumes to reach surface waters and relative return flow concentrations, but do not consider the assimilative capacity of such water bodies, which will likely be significant. To conduct this environmental assessment, the irrigation return flows and constituent concentrations are required, which are calculated based on prevailing groundwater gradients, hydraulic conductivities, and porosities. All of these parameters in the current model are based on regional assumptions (geological map) and should ideally be locally refined. Additionally, the flow rate or volume of the receiving water body, with its background concentration and DWS established, the Resource Quality Objective also needs to be considered. Nonetheless, the assessments performed provided valuable insights into key considerations for establishing mine water irrigation schemes from an environmental perspective.

CHAPTER 4: ECONOMIC ASPECTS OF LARGE-SCALE MINE WATER IRRIGATION IN THE EASTERN BASIN

4.1 INTRODUCTION

Irrigation has been proposed as a cost-effective option for managing mine water from the Witwatersrand Goldfields, with the potential to create livelihoods. Preliminary assessments by van der Laan, et al. (2014) indicated that irrigation with Witwatersrand Goldfield mine waters was feasible. Spatial analyses suggested that there was sufficient land in the built-up Witwatersrand region to support irrigated crop production. The economic analyses indicated that mine water irrigation could be profitable if appropriate cropping systems are selected. However, more detailed analyses were recommended to better understand the economic sustainability, potential socioeconomic impacts and scalability of mine water irrigation in the Witwatersrand Goldfields. The assessment of these economic aspects of mine water irrigation was undertaken in three phases as follows:

- Phase 1: Market analysis
- Phase 2: Development of an actual farm
- Phase 3: Analysis of economic sustainability, socioeconomic impacts and scalability of mine water irrigation

4.2 MARKET ANALYSIS

Market analyses were performed using the multi-market Partial Equilibrium (PE) model developed by the Bureau for Food and Agricultural Policy (BFAP) over several years. After initially starting with an ad hoc combination of country and commodity coverage driven by specific research requests for forward-looking analysis in the region, the first comprehensive structure for grains and oilseeds across 8 countries was established in 2012. Over time, the model has been utilised in various research projects and expanded to cover 12 countries, with commodity coverage ranging from 1 to 56 in each country (South Africa), and relevant sectors linked through both competition for resources and input-output relationships. For instance, livestock is linked to grains through animal feed, so scenarios that affect the livestock sector spill over into grains, and vice versa.

The multi-market model is a dynamic, recursive partial equilibrium framework based on balance sheet principles to establish equilibrium, in which total supply (production, imports, and stocks) equals total demand (consumption, exports, and ending stocks) for each product. This approach, together with analyses of market prices, provides the backbone for detailed market analysis, which forms the foundation of the market-led approach of this project. The strengths of the partial equilibrium framework lie in the ability to capture intricate market and policy details that closely mimic the situation for specific commodities. This also enables detailed scenario analysis when changes occur in any of the existing variables or relationships.

Model specification is generally based on well-accepted supply-and-demand structures, with prices determined by a combination of import or export parity and domestic supply-and-demand dynamics, depending on the market situation for each commodity. The modelling framework ensures consistency in supply and demand relationships and provides price impacts of alternative scenarios, as well as dynamic supply and demand responses over time.

Parameterisation is based on a combination of econometric estimation and elasticity assumptions derived from a literature review, theoretical consistency, and specialist judgement. The model is calibrated using historical data, with the period determined by data availability and consistency. For most commodities, the calibration period ranges from 2000 to 2022.

The reliance on historical data, both for estimation and calibration, implies that significant emphasis must be placed on the quality of the historical data used to feed the model. Initial commodity balance sheets were compiled based on a range of secondary data sources. While the official national data provided the starting point for balance sheet compilation, complementary data from the other listed sources provided opportunities for validation and alternatives where required.

4.2.1 Baseline summaries

The BFAP Baseline presents an outlook of agricultural production, consumption, prices and trade in South Africa for the period 2023 to 2032. The outlook is generated using BFAP's system of models, and amid the current turmoil in both global and domestic markets, it aims to provide insights to support decision-making. The information presented is based on assumptions on a range of economic, technological, environmental, political, institutional, social and international market factors. Amongst these is the key assumption that the current energy crisis in South Africa will improve in the medium term as investments in private generation capacity come to fruition. Load shedding, however, remains a short-term constraint. Furthermore, the baseline assumes that normal weather conditions will prevail in Southern Africa and worldwide; therefore, yields per hectare grow steadily over the baseline as technology improves.

Assumptions regarding the outlook for macroeconomic conditions are based on a combination of projections from the International Monetary Fund (IMF), the World Bank, and the Bureau for Economic Research (BER) at Stellenbosch University. Baseline projections for world commodity markets were generated by the Food and Agricultural Policy Research Institute (FAPRI) at the University of Missouri. Once the critical assumptions are captured in the BFAP system of models, the Outlook for all commodities is simulated within a closed system of equations. This implies, for example, that shocks in the grain sector are transmitted to the livestock sector, and *vice versa*. Therefore, for each commodity, important components of supply and demand are identified, after which an equilibrium is established through balance sheet principles by equating total demand to total supply.

The baseline takes the latest trends, policies and market information into consideration and is constructed to present a picture of equilibrium in agricultural markets, given the assumptions made. ***However, markets are highly volatile, and the probability that future prices will not match baseline projections is therefore high. Given this uncertainty, the baseline projections should be interpreted as one possible scenario in which temporary factors play out in the short run, and permanent factors drive structural shifts in agricultural commodity markets over the long run.*** The Baseline, therefore, serves as a benchmark against which alternative exogenous shocks can be tested and interpreted. In addition, the Baseline serves as an early-warning system to inform role-players in the agricultural industry about the potential effects of long-term structural changes on agricultural commodity markets, such as the impact of a sharp increase in input prices or technological improvements on supply response.

To summarise, the Baseline does NOT constitute a forecast, but rather represents a benchmark of what could happen under a particular set of assumptions. Inherent uncertainties, including policy changes, weather, and other market factors, make it highly unlikely that the future will match baseline projections. Recognising this, BFAP incorporates scenario planning and risk analysis to understand the underlying risks and uncertainties of agricultural markets. Farm-level implications are included in the commodity-specific sections, and the scenarios and risk analyses illustrate the volatile outcome of future

projections. Additional stochastic (risk) analyses are not published in the baseline, but are prepared independently on request for clients. The BFAP Baseline 2023 should thus be regarded as only one of the tools in the decision-making process of agricultural sector role players, and other sources of information, experience, and planning and decision-making techniques have to be taken into consideration.

The baseline 2023 summary for the crops selected in Section 1.3 is presented in the sub-sections that follow.

4.2.2 Soybeans in the context of summer grains and oilseeds in South Africa

Oilseed production growth has been strong, with a near 100 000-hectare expansion in soybean area, propelling a 22% growth in production for 2023, following an 18% expansion in 2022. This implies that soybean production has more than doubled since 2020, exceeding 2.8 million tonnes by 2023. Expansion was fuelled by higher prices, in line with global dynamics, combined with exceptional yields as producers optimised seed variety choices, particularly in the drier western parts of the country. The sharp increase in production, combined with concerns about port efficiency, pushed soybean prices below export parity in early 2023. Despite the projected year-on-year price decline of more than 15%, the gross value of soybean production has risen for the 4th consecutive year, driven by a substantial increase in production volume.

Strong profitability in summer crop production in recent years was a key factor that drove summer crop area expansion, to the extent that the total summer crop area in 2022 was the highest since 2000. Likewise, the reduction in producer margins over the outlook, as prices decline and yields normalise, is a key factor contributing to the expected consolidation in summer crop area over the next 2-3 years, when total summer crop area is expected to contract by roughly 200 000 hectares. The relative composition of summer crops across the total area will also reflect their relative profitability, as well as the popularity of different cropping rotation systems in other parts of the country. Grain area is expected to consolidate, while oilseed area is expected to expand further, albeit at a much slower rate than in recent years. Most of the soybean area expansion in recent years occurred in the western parts of the country, replacing both white maize and sunflower. Within the norms of crop rotation systems, this area will likely remain under soybeans, with total area expanding further in the medium term following a brief consolidation as prices decline in the short term.

Soybean yields are expected to continue the rapid gains achieved in recent years, despite area expansion (see Figure 4.1), reflecting the release of the latest seed technologies (improved germplasm and GM traits) following the introduction of the breeding technology levy. Planting varieties best suited to specific areas has been instrumental in enhancing soybean performance in the drier western parts of the country, and producers have refined production practices, unlocking significant potential.

Soybean production has grown to the extent that prices are expected to remain at export parity levels, as South Africa continues to export significant volumes (Figure 4.1). This is likely, as the combination of area expansion and further yield gains will enable faster production growth than the domestic expansion in animal feed demand. Despite these high export volumes, soybean processing capacity will likely need to expand by midway through the coming decade to process projected volumes. For investment into additional processing capacity to occur, the current electricity crisis would likely need to improve, and this is only expected in a few years, when current investment into private generation starts to contribute meaningfully to the national grid.

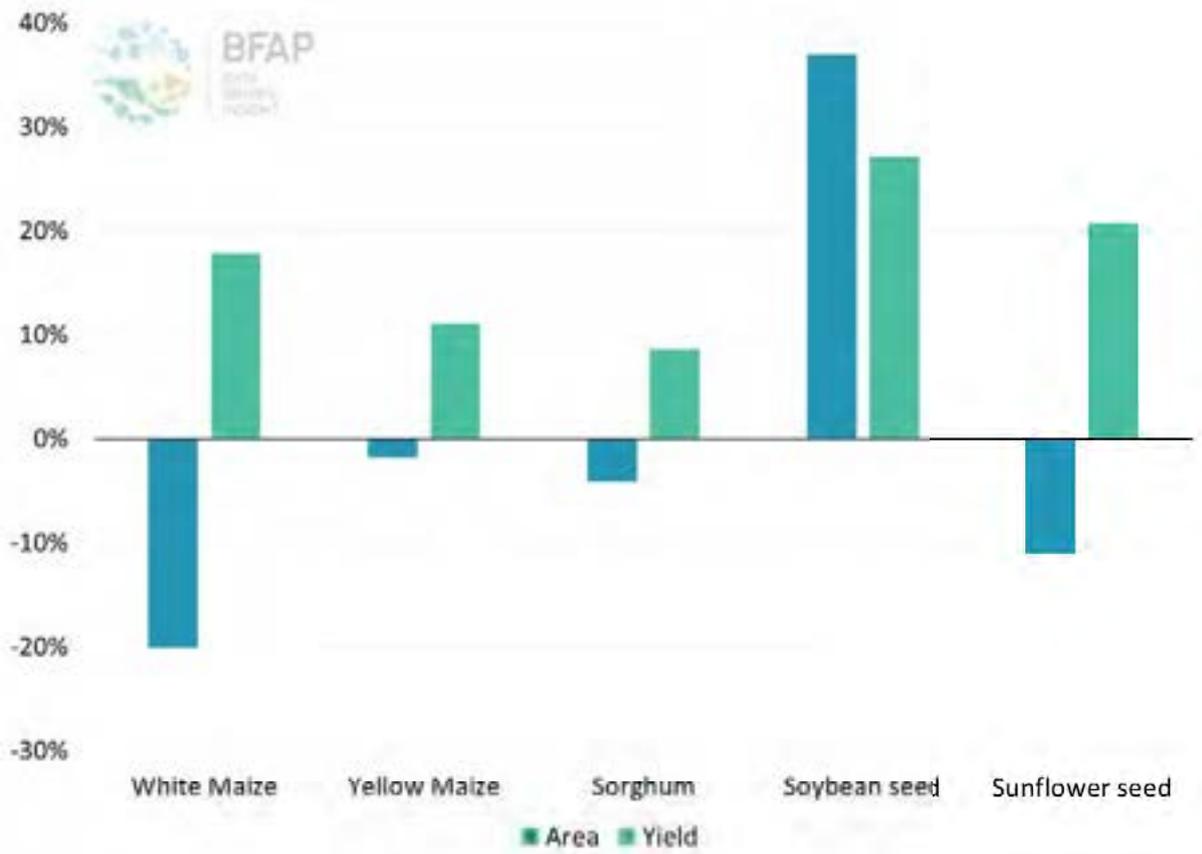


Figure 4.1: Percentage expected change in area and yield for major summer crops: 2032 vs 2020-2022 base period

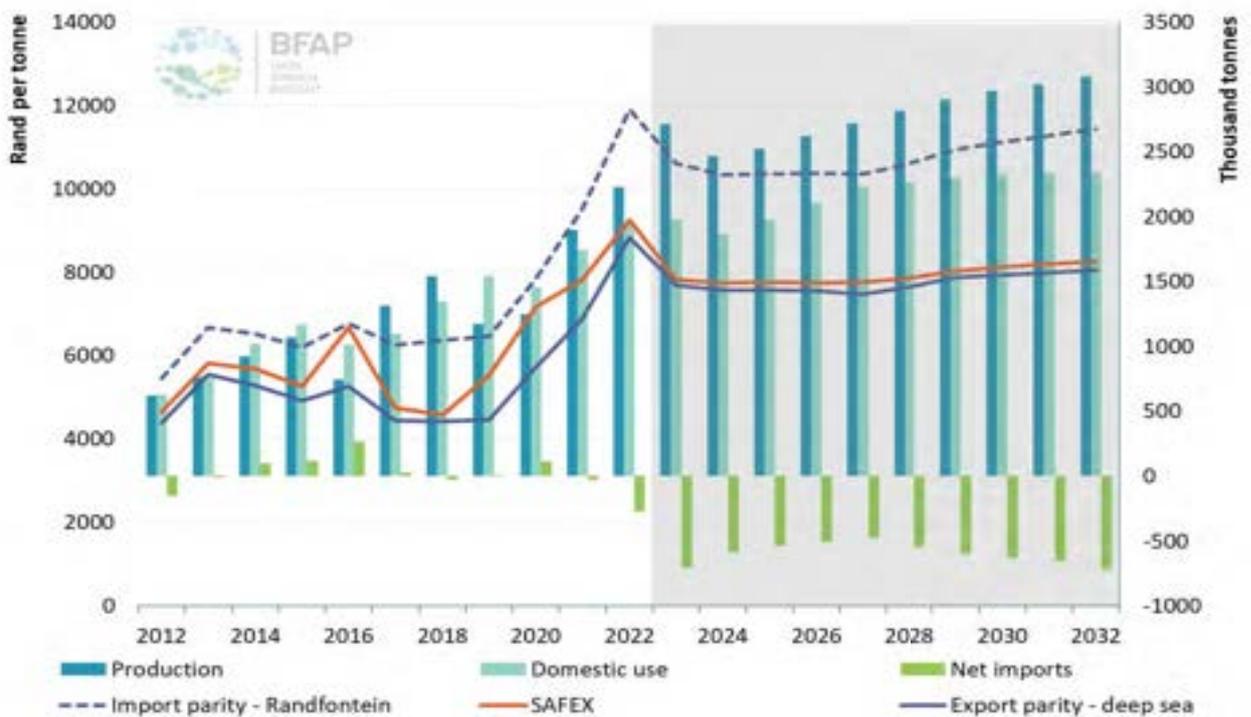


Figure 4.2: Soybean production, consumption, trade and prices: 2012-2032

The past three years have been among the best on record in South Africa's summer crop sector, driven by a rare combination of large domestic crops and high prices, stemming from international dynamics. Global prices have, however, entered a downward cycle, which is also expected to spill over into South African markets, given surplus production of most major summer crops. This implies that margins will become tighter over the next few years, requiring continuous innovation to remain on top of the productivity curve. Significant investment stemming from the successes of the past few years could improve producers' resilience during the next downward cycle. Still, the energy crisis will pose significant challenges across the value chain, constraining sector competitiveness and adding substantially to capital and operational expenditure.

4.2.3 Oilseed and oilseed product demand in South Africa

Growth in oilseed processing has been a critical enabler of import replacement for both protein meal and oilcake used in animal feed rations, as well as for vegetable oils. To illustrate the extent of import replacement that has occurred, Figure 4.4 provides an aggregated summary of oilcake supply and demand. It shows total consumption in 2012 and 2022, a projection for 2032, and the relative contributions of soybean, sunflower, and canola oilcake production and imported oilcake. Further replacement in oilcake imports is limited, firstly because of the extent to which it has already occurred, given that soybean oilcake imports already fell below 200 000 tonnes by 2022. Secondly, the relative competitiveness of products processed in the interior (largely the Reef) is often still lacking in coastal markets, particularly in the Western Cape, due to high transport costs. While some penetration into coastal regions occurred in 2023 when domestic oilcake was offered at a substantial discount to imported products, some imports are still happening, with domestically produced cake exported cross-border to neighbouring markets. Thirdly, the current energy crisis is not conducive to improved processing competitiveness, as it adds to the costs of operating on alternative energy sources. This suggests that processing capacity may only expand once these challenges are solved. By 2032, oilcake imports are expected to remain close to 2022 levels, with unprocessed soybeans exported instead.

While sunflower and canola are crushed predominantly for the vegetable oil market, canola in particular provides an attractive alternative source of protein for animal feed, particularly in the Western Cape, where it is produced and processed. By 2032, canola oilcake production is expected to rise by almost 70%, but this growth is from a small base and therefore amounts to only 60 000 tonnes. This will likely be taken up by dairy and pork producers in the Western Cape.

Vegetable oil consumption growth has slowed in recent years due to a combination of limited consumer spending power and sharp price increases. While consumer spending remains under pressure, prices are currently declining, which signals improved demand prospects in future. By 2032, total vegetable oil consumption is expected to rise by 22% from 2022 levels, but the biggest share of total use is attributed to imported palm oil (Figure 4.5). South Africa does not have the agroecological conditions to produce palm oil, and its popularity in both the food service sector and for industrial use is underpinned by its favourable relative affordability. Palm oil imports are expected to rise from just over 500 000 tonnes in 2022 to more than 580 000 tonnes by 2032. While South Africa's production of soybean, sunflower and canola oil is expected to rise, processing growth is substantially slower than in the past decade. So, imported oils will still account for around two-thirds of additional vegetable oil consumption in South Africa by 2032 relative to 2022.

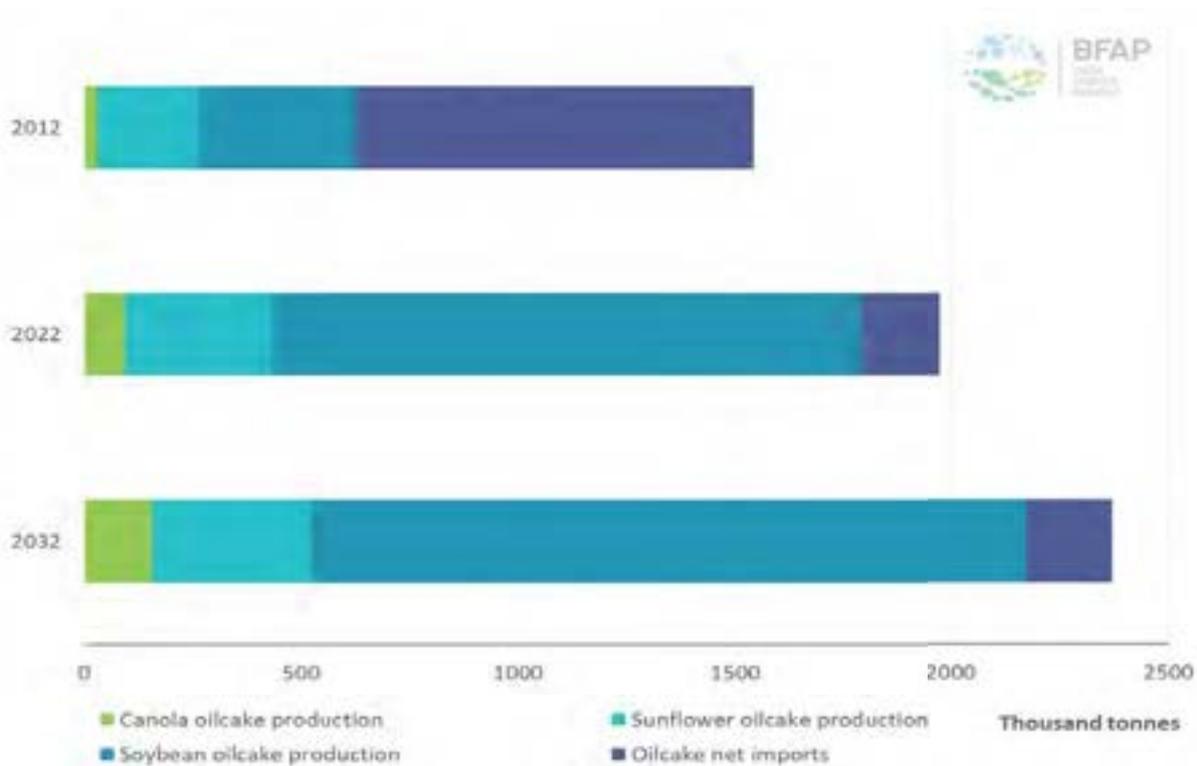


Figure 4.3: Oilcake supply and demand in South Africa: 2012-2032

4.2.4 Canola in the context of winter grains and oilseeds production

The winter grains and oilseeds industry in South Africa has grown remarkably over the past decade, with the combined gross production value for wheat, barley and canola increasing by 9% per annum. Over the period from 2017 to 2021, industry revenue rose by 67% in 2022, contributing an additional R7.7 billion. The increase was driven by robust performance in the wheat and canola industries, which added R6.0 billion (+69%) and R1.3 billion (+141%) respectively. Although much of this growth was underpinned by higher prices, volumes also increased due to a combination of area expansion and yield gains.

In 2022, the canola production area increased by nearly 42 000 hectares relative to average production areas from 2017 to 2021, with production volumes expanding by 60%. Total domestic production exceeded 210 000 tonnes in 2022, from just 93 468 tonnes in 2017. Industry efforts to obtain improved seed varieties over the past decade propelled productivity growth, yielding significant improvements in profitability relative to alternative winter crops. This expansion was supported by high crop prices in 2021 and 2022. Risks associated with barley production, particularly quality risks, further contributed to the shift to canola.

Although the canola area is projected to stabilise over the next 2-3 years as prices decline, further expansion is projected over the second half of the outlook period. Assuming the introduction of new and improved seed varieties and continuous availability of these products, canola area is projected to reach 146 000 hectares by 2032, adding a further 56 000 hectares to the current area.

In response to high wheat prices and favourable soil moisture in 2022, the area under wheat production in the summer rainfall regions, particularly in the Free State, increased 2022. The expansion followed a period of considerable variability in the area under production, which fluctuated between 70 000 and 110 000 hectares since 2014. With increasing competition from soybeans, persistent risks associated with wheat grown under dryland conditions, and declining commodity prices, wheat area in the summer

rainfall region is projected to contract in 2023 and 2024, then stabilise at around 85 600 hectares in the medium term. Similarly, wheat area under irrigation is projected to decline by 0.8% per annum over the baseline period, reaching 89 700 hectares by 2032. This represents a decline of 3 500 hectares relative to the 2018-2022 average, as it continues to compete with perennial crops for water, particularly in the Northern Cape. Note that these baseline projections assume no additional irrigation water availability, and the whole-farm model will show whether the addition of irrigation enterprises in existing farming units in the region would compete well enough to be attractive and adopted.

The fastest growth over the outlook period is anticipated for the canola industry, with yields per hectare projected to increase by 18% and area by 47% by 2032. Although the small base tends to amplify these growth rates, the continuous introduction of improved varieties, together with local efforts to boost seed supply (and availability), will promote yield growth over the outlook. The outcomes and successes of these industry efforts are already evident in the step-change in yields since 2020.

The combination of productivity growth and area expansion is set to boost local canola production by 78% over the coming decade. By 2032, production could reach 341 400 tonnes, an increase of more than 190 000 tonnes from 2020-2022 levels (Figure 4.6). The expansion will require additional investment in processing facilities, while exports are projected to increase over the outlook period. Additional canola processing capacity can help replace imported vegetable oil, and there are ample market opportunities for oilcake in the Western Cape dairy and pork industries.

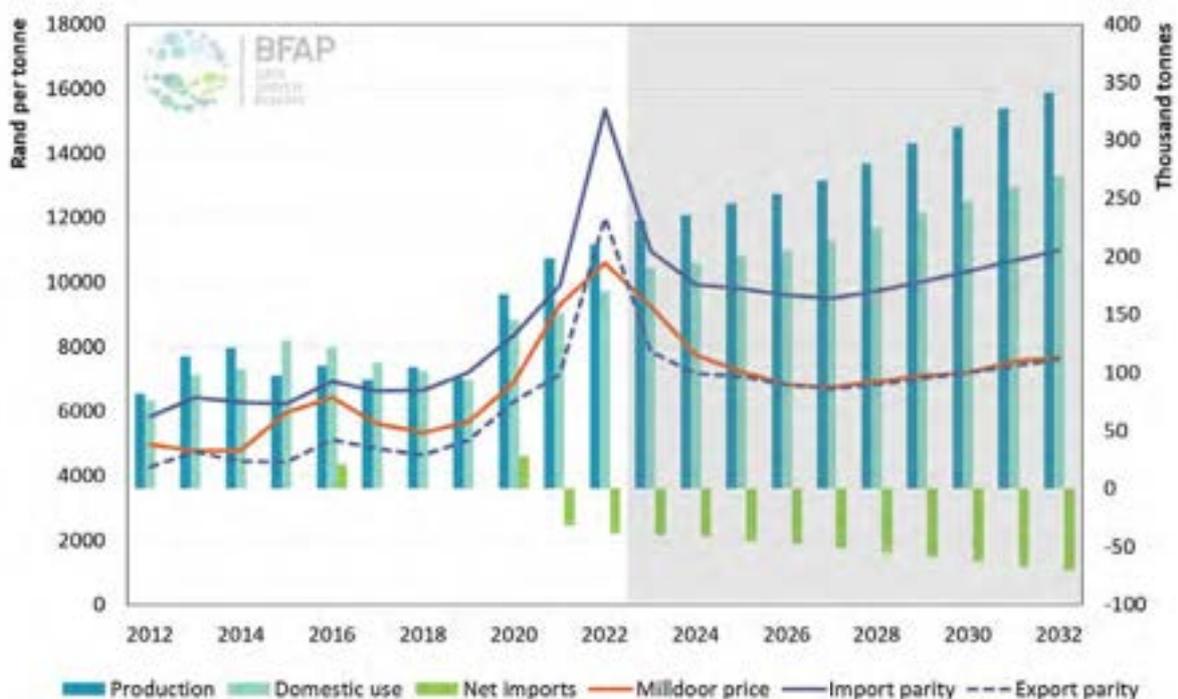


Figure 4.4: Canola production, consumption, trade and prices: 2012 – 2032

4.2.5 Sweet sorghum silage

The silage market is a free market, with prices agreed upon by the supplier and buyer (with no officially published/listed prices). The trackability of historical prices is very low due to the nature of the market, where many players produce silage with integrated value chains or intentionally keep prices confidential.

Currently, silage is produced mainly for local livestock farmers, with limited exports over the past three years. Silage production either takes place internally (on the producer's own farm) for a vertically integrated business or is purchased through forward contracts between producers and off-takers (typically feedlots/large dairies). In South Africa, off-takers mainly include ruminant livestock (hooved herbivorous grazing mammals such as cattle and sheep) farmers, with fodder included in cattle diets for dairy and meat production or reproduction purposes. Furthermore, some bales, especially lucerne, are exported as feedstock for international ruminant consumption. Significant investment is currently underway in South Africa to develop fodder crop-based biogas production capacity, which will introduce a new market channel for silage. Figure 4.7 shows the current value chain of silage.

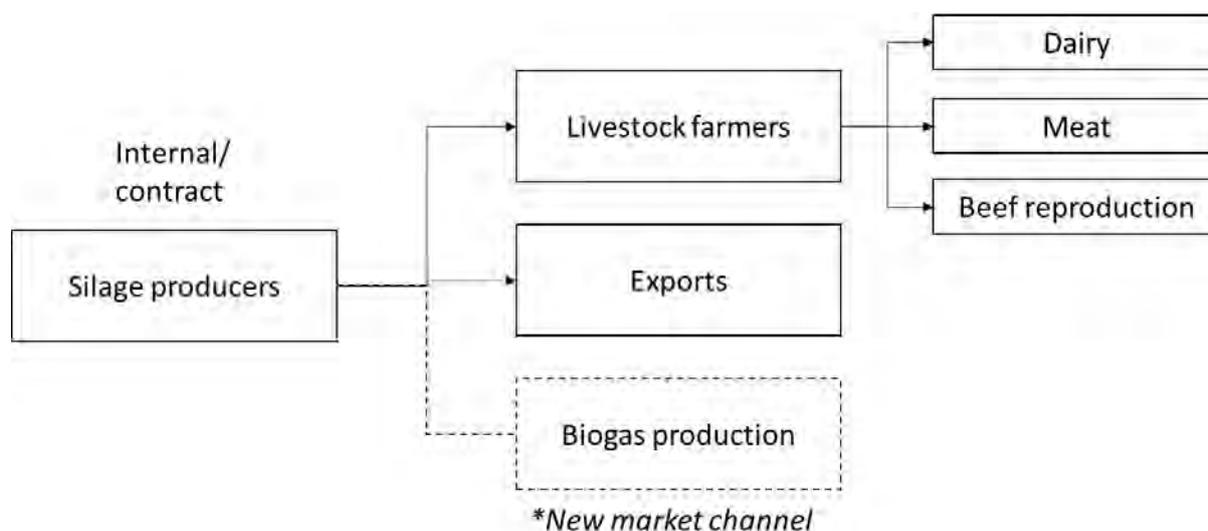


Figure 4.5 Silage value chain map.

Industry role-players supplied sample prices for the 2022 production season, as shown in Table 4.1 . Current market prices range from ZAR880/tonne to ZAR1 300/tonne, depending on factors such as distance, silage form (bagged, re-baled, fresh high-compact wrapped bales, or truckloads), and supplier and off-taker agreements. The rest of the silage market is on a direct-contract basis, typically following a 12%–18% price linkage to the SAFEX maize price.

Table 4.1 Market prices of silage in 2022/2023.

Crop	Form	Cost without transport	Cost with transport
Sweet sorghum	Silage Bale	ZAR1150/tonne	ZAR40/load km
Maize	Silage on-farm bunker	ZAR880/tonne	No additional cost

4.3 WHOLE FARM MODEL

4.3.1 Model description

The whole-farm model was built using BFAP's FINSIM, which simulates the financial performance of an entire farm and accounts for the farm's direct and indirect overhead structure. The farm is simulated over 8 years to provide a possible future view, incorporating BFAP sector model projections.

BFAP's farm and resource analytics experts conduct in-depth financial and business analyses of farming operations in Southern and Eastern Africa. Examples include finance-economic integrated analysis, farm financial budgeting, whole-farm planning, and investment and risk analysis. The actual whole-farm model is customised here for the Eastern Basin Mine Water Irrigation enterprises and rotations (enterprise-specific direct costs) within a given assumed farm structure (i.e. capital investments, overheads / indirect costs).

Setting up the BFAP whole-farm model involved the following datasets and assumptions:

- Enterprise specifics: Area, yield, price & direct costs (i.e. direct input costs like seed, fertiliser and field preparation costs)
- Overhead inclusion:
 - Non-allocatable costs (labour, management, electricity, bank, etc.)
 - Assets/liabilities
 - Asset replacement

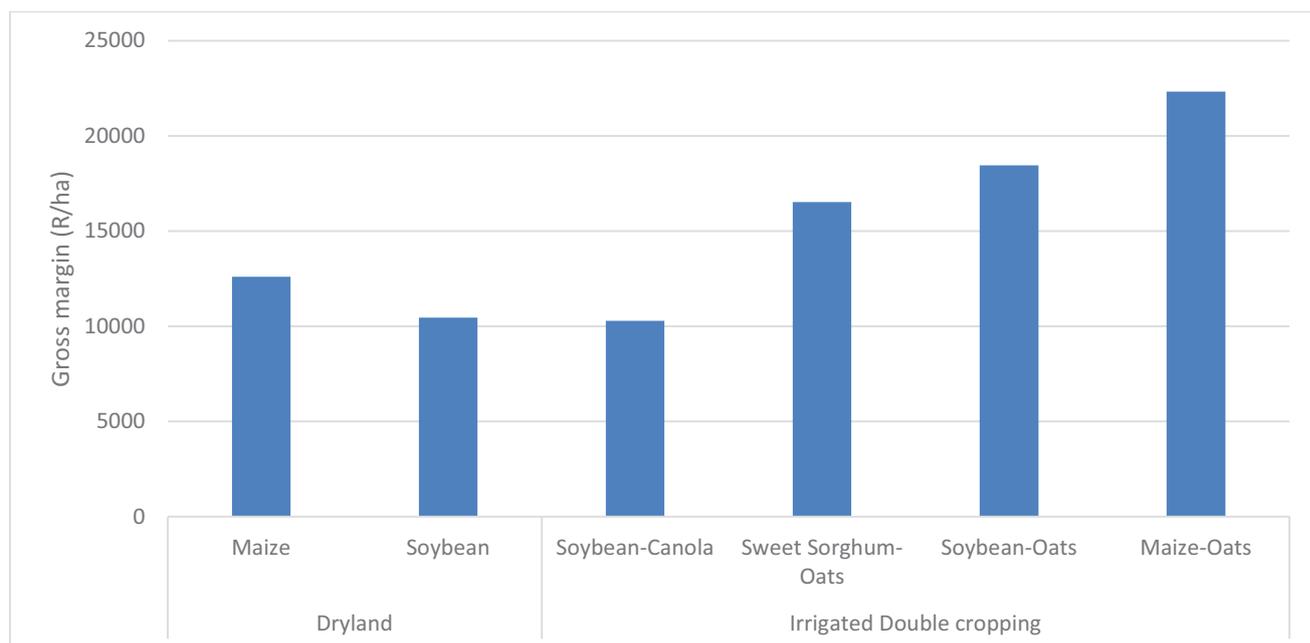


Figure 4.6 2023 to 2030 Average Gross Margin per Hectare per Rotation

Gross margins for the following crop production systems were developed for the 2022/2023 production season to investigate the farm-level economic feasibility of irrigation intensification in the Eastern Basin region:

- Dryland maize (part of the **original** farm crop mix)
- Dryland soybeans (part of the **original** farm crop mix)
- Irrigation maize (introduced as part of the **intensified** crop mix with **treated** water)
- Irrigation oats (introduced as part of the **intensified** crop mix with **treated** water)

- Irrigation maize (introduced as part of the **intensified** crop mix with **untreated** water)
- Irrigation oats (introduced as part of the **intensified** crop mix with **untreated** water)

4.3.2 Revenue assumptions

Table 4.3 lists the assumptions used for crop yields and prices in the revenue calculation. The yields were based on typical average yields for the different crops, for both dryland and irrigated production, and were cross-checked with producers in the region. It is important to note that yields may be higher or lower in some years due to agriculture’s exposure to a wide range of variables.

The University of Pretoria (UP) performed long-term (45-year) modelling using the IrrigWQ Decision Support System developed by du Plessis et al (2023) to determine irrigation requirements and assess the effects of mine water irrigation on crop yield (Table 4.2). It was predicted that maize yield would be slightly affected by irrigation with mine waters. A relative yield decline of 1.4% expected for maize irrigated with HDS-treated mine water, and a relative yield decline of 1.8% for maize irrigated with untreated mine water. Irrigation with mine waters was predicted to have no impact on oat yield. The crop prices were calculated by accounting for transport and other deductions from SAFEX prices to arrive at a farm-gate price in the Eastern Basin.

Table 4.2 Modelled irrigation requirements for the maize– oats cropping system and effects of mine water irrigation on crop yield

Parameter	Maize (Summer)	Oats (Winter)	Total
Gross irrigation (mm/season)	276	549	825
Rainfall (mm/season)	506	99	648
Yield penalty treated water (%)	1.4	0	
Yield penalty untreated water (%)	1.8	0	

The model assumed that oats are sold as square-shaped baled hay. This is to quantify the profitability and additional income that the oats can potentially generate. Furthermore, oats are currently produced on dryland, resulting in significantly lower yields. Hence, additional volumes will need to enter the formal market, as the farm’s livestock cannot consume the total harvest, especially not at an economically feasible rate. Other options would be big packs or silage. However, these products are not yet typically/widely produced in South Africa, and further research would be needed to determine the respective opportunities.

Table 4.3 Revenue Assumptions

System	Crop	Yield (t/ha)	Crop Price (R/ton in 2023)	Product description
Dryland	Maize	8.3	R3 686	Harvested grain
	Soybean	3	R8 322	Harvested grain
Irrigated (HDS treated water)	Maize	11.83 (1.4% penalty)	R3 686	Harvested grain
	Oats	10 (500 bales)	R3250 (R65/bale)	Baled hay
Irrigated (Untreated water)	Maize	11.78 (1.8% penalty)	R3 686	Harvested grain
	Oats	10 (500 bales)	R3250 (R65/bale)	Baled hay

The revenue (yield multiplied by farm-gate price) for each crop is illustrated in Figure 4.9. Due to higher yields under irrigation, the revenue from maize and oats is higher than under dryland production. The revenue from oats remained the same with treated or untreated water. In contrast, the revenue from maize declined slightly (0.4%) with untreated water due to a larger negative yield impact, as indicated in Table 4.3.

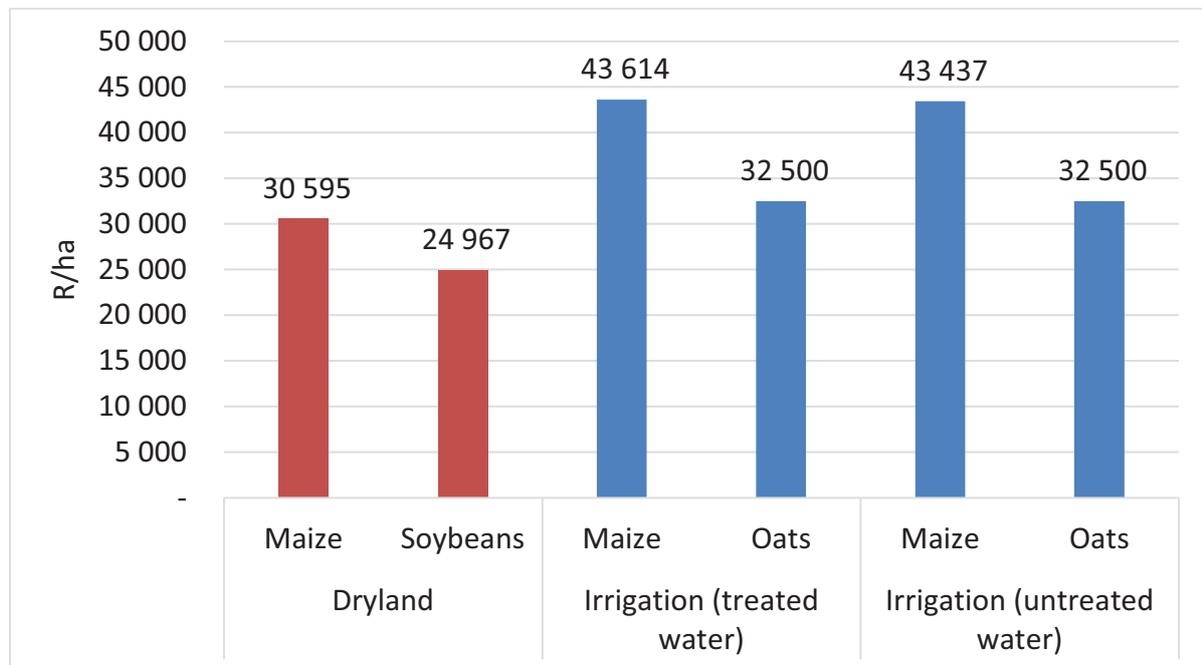


Figure 4.7 Revenue per hectare for selected crops in 2023

4.3.3 Direct cost assumptions (including irrigation costs)

The following direct costs were included when calculating the gross margin per hectare per crop:

- Contract cost, crop insurance, fertiliser, fuel, herbicide, lime, marketing costs, repairs and maintenance (directly allocated), storage costs and unforeseen expenses, seasonal labour, seed and irrigation costs (water, electricity and scheduling, see following point for details).
- Cost of irrigation is added to the total direct cost for the crops produced under irrigation (maize and oats). The irrigation cost per crop type varies, given that each crop has its specific water usage, as indicated in Table 4.4. The cost of irrigation includes:
 - R2.136/mm operational cost per hectare for using the water infrastructure to get the water from the mine to the farm. This includes repairs and maintenance costs, but not capital investment costs¹ (inflated from AMD water for irrigation report, 2013/14)
 - R7.26/mm electricity cost per hectare, to pump the water from the point of supply (river or pipe which conveys the water from the mine to the producers) to the pivot.

¹ Note, that the type, cost and modular setup (main pipes, water storages solutions, irrigation scheme setup etc.) of how the treated water will reach the farmer is not accounted for in this model. This is additional research that would need to supplement this work from an infrastructure planning perspective should such a project be undertaken.

- R1.05/mm repair and maintenance cost per hectare for pivot infrastructure
- R114/ha water scheduling cost (once-off, does not vary per water usage or crop type)
- The mine waters are expected to be somewhat scaling, which may affect future pumping costs. However, the scaling effects were not accounted for in this study. The project team consulted with a civil engineer (Dr Lois Coetzee) for assistance with modelling the scaling effects. It was advised that it would not be feasible within the scope of this high-level study, as the modelling inputs are highly site-specific and difficult to estimate, possibly requiring a separate study. It is recommended that modelling of mine water effects on the irrigation system be considered in future studies, should implementation of mine water irrigation be considered, where more site-specific assessments are required.
- The cost of lime is presented in Table 4.5 for crop production on dryland, as well as under irrigation with treated and untreated water. Because the typical farm already applies lime to its soils (at lower rates), only the cost of the additional lime was included, not the extra cost of applying lime to the field.
 - Additional lime application rates, determined based on the acidity of the waters, were provided by UP.
- Contract costs were only assumed for the harvesting of oats, as it is not a typical crop in the area (partially produced, but not to such an extent that personal harvesting equipment would be available). Harvesting of maize is not contracted because it is assumed that the farm already has a maize harvester, given that maize is already produced on dryland.
- Furthermore, it is assumed that the typical farm has the required equipment to conduct the remaining operations (planting, fertiliser application, spraying, etc), and there is thus no impact on the farm's current fleet. It is assumed that the growing periods of the two crops (maize in summer and oats in winter) do not overlap, and hence sufficient equipment is already available to cultivate both in a single year.
 - Due to the area having a high crime rate, R1 000 per hectare security cost is allocated for alarm systems. Furthermore, an investment in fencing and security cameras was assumed as a medium-term investment.

Table 4.4 Irrigation-related Input Cost Assumptions (excluding other direct costs)

	Dryland		Irrigation (treated water)		Irrigation (untreated water)	
	Maize	Soybean	Maize	Oats	Maize	Oats
Water Usage (mm)	0	0	276mm*	549mm	276mm*	549mm
Water Cost (R2.36/mm/ha)	R0	R0	R652	R1 296	R652	R1 296
Electricity Cost for Water (R7.26/mm/ha)	R0	R0	R2 174	R4 319	R2 174	R4 319
Pivot R&M Cost (R1.05/mm/ha)	R0	R0	R291	R576	R291	R576

	Dryland		Irrigation (treated water)		Irrigation (untreated water)	
	Maize	Soybean	Maize	Oats	Maize	Oats
Water Scheduling Cost (R114/ha)	R0	R0	R114	R114	R114	R114
Total Cost of Irrigation (R/ha)	R0	R0	R3 231	R6 305	R3 231	R6 305

*The remaining water requirement is obtained through rainfall in summer

Table 4.5 Cost of additional lime application, assuming a lime cost of R0.52/kg (excluding other direct costs)

System	Crop	Additional lime required (kg/ha)	Lime application cost (R/ha)
Dryland	Maize	0	R0
	Soybean	0	R0
Irrigated (HDS treated water)	Maize	35	R20
	Oats	69	R39
Irrigated (Untreated water)	Maize	452	R258
	Oats	899	R512

Figure 4.10 illustrates the total direct cost per hectare per crop cultivated. As with revenue, the crops produced under irrigation also have higher direct allocatable costs than the dryland crops (i.e. direct irrigated maize cost is 71% higher than direct dryland maize cost), and the crops with treated water have a lower direct cost than with untreated water (because of the additional lime cost; Maize: -0.77%, oats: -2.1%).

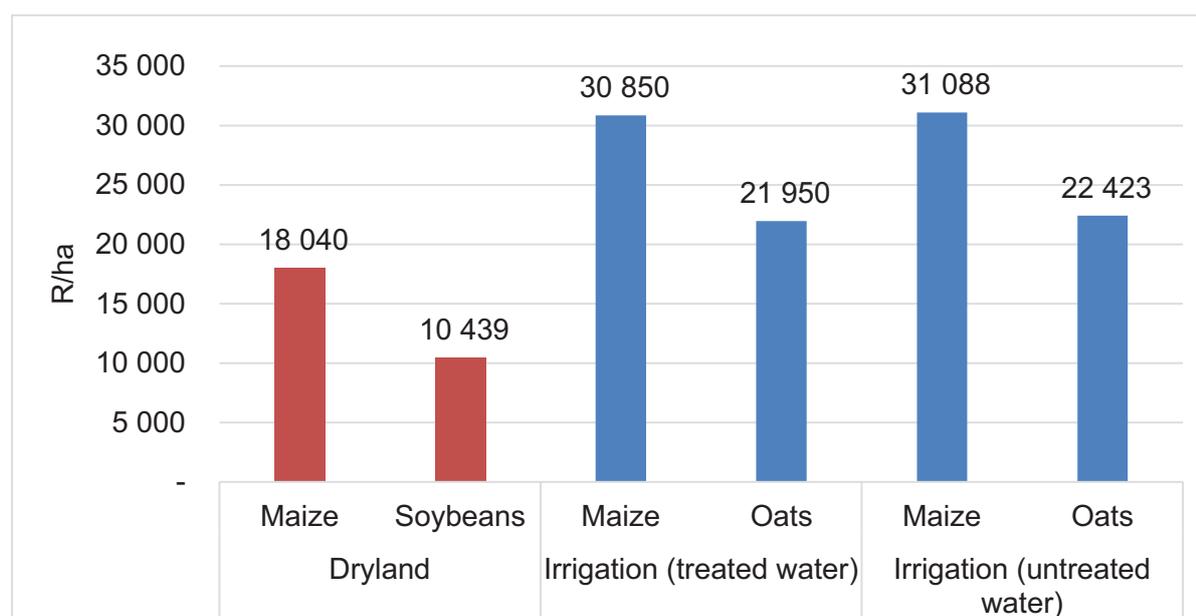


Figure 4.8 Total cost per hectare for selected crops in 2023

4.3.4 Relative profitability of enterprises

Figure 4.11 illustrates the gross margin per hectare per crop cultivated in 2023, only taking direct costs into account (revenue minus direct costs). On a single crop basis, dryland maize and soybean production performed better than maize and oats under irrigation. This is due to additional costs incurred by the irrigated cropping system, which are not offset by the irrigation yield gain (which is limited by seed technology improvements and climatic conditions). However, since irrigated maize and oats are part of a crop rotation system, the farm will receive combined profits from both crops, resulting in the highest profit per hectare (as illustrated in the additional bar). Furthermore, the risk reduction associated with irrigation is a significant factor to consider. However, a considerable investment cost is required for irrigation. The irrigation investment's potential gain or loss to the farm's overall profitability (economic/financial sustainability) is analysed and discussed in the following section.

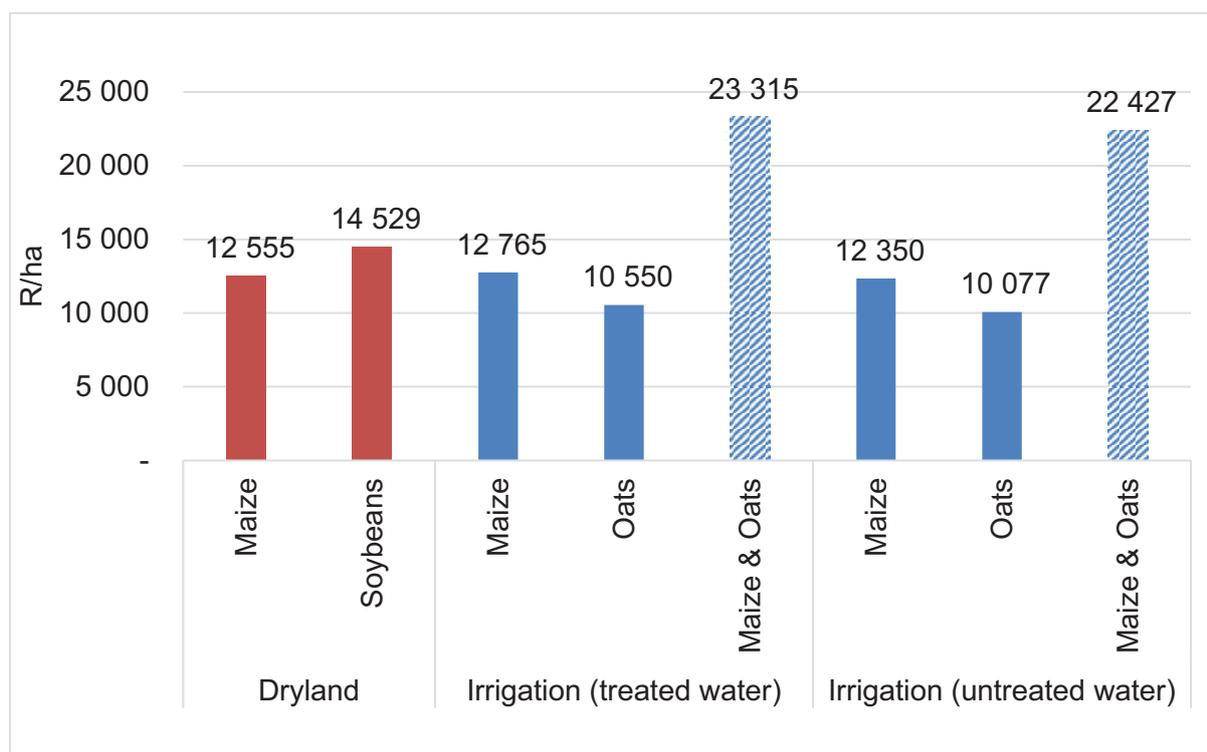


Figure 4.9 Gross margin per hectare for selected crops in 2023

The gross margins of the crops were calculated using actual yields, prices and direct costs for 2023 and 2024, and projected for the next six years (2025 to 2030), taking into account the BFAP sector model's price, yield and change in cost projections². The BFAP suite of models does not include a sector model for oats. However, it was assumed that oats would follow the same crop price and yield trend as yellow maize, given that oats are also linked to the feed industry. Projected gross margins were used in the whole-farm-level model to generate net farm income for the illustrated eight years under different scenarios. This is further discussed in the following section.

² The BFAP sector model was also updated since Deliverable 5, to include the most recent macro and micro economic expectations and projections given the latest global and local developments.

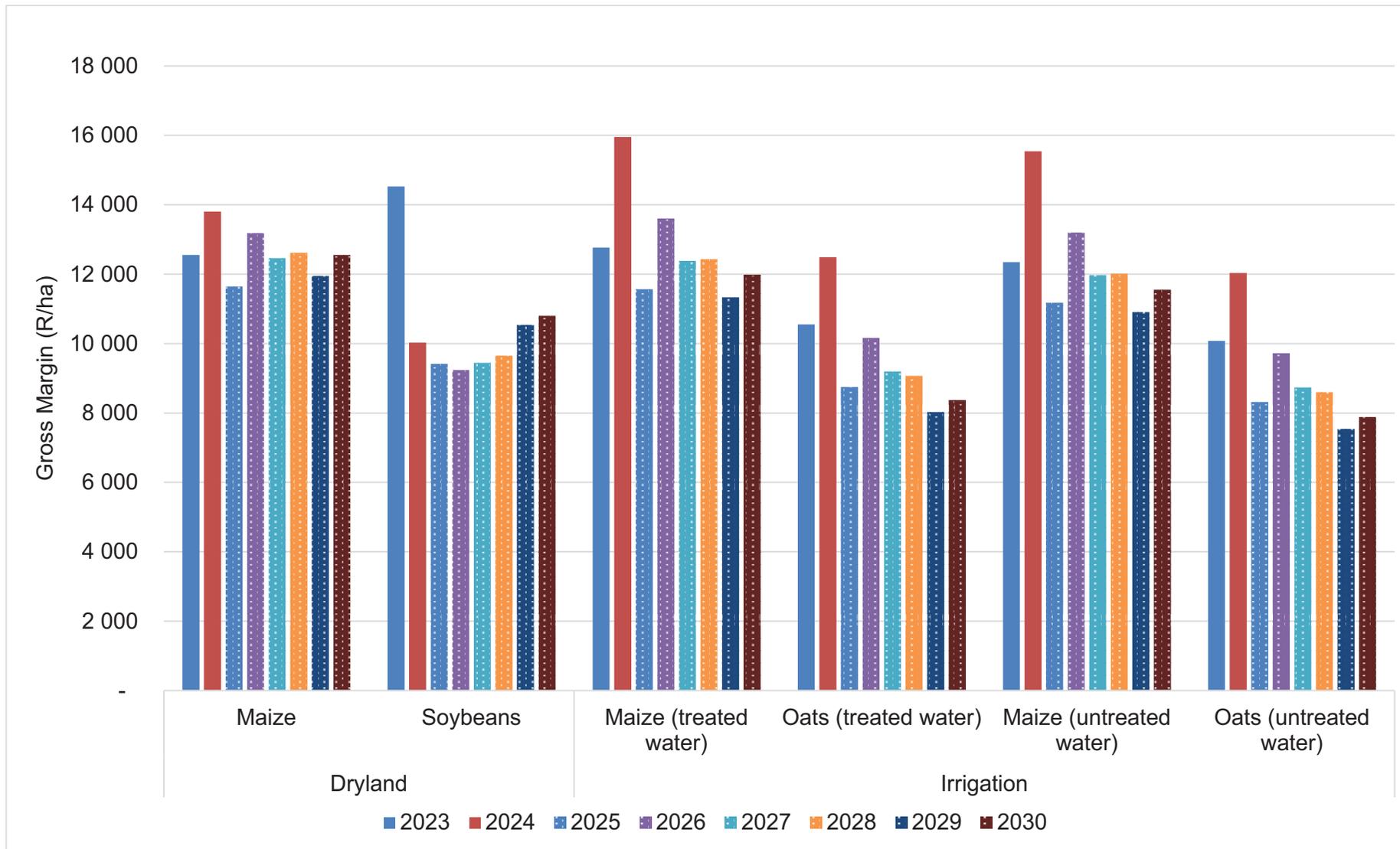


Figure 4.10 Projection of Gross Margins per Hectare

4.3.5 Overhead cost assumptions

To model a whole farm-level income statement, the direct crop gross margins from the previous section are applied to the total farm area (taking rotation into account) in combination with overhead costs that need to be incurred for day-to-day farm operations. Furthermore, the assets and liabilities need to be included in the model to capture the farm's complete cash flow and balance sheet (for a typical farm).

- The following **overhead costs** of a typical farm for the Eastern Basin were compiled and incorporated into the model framework. They include:
 - Accident insurance for employees, auditor, bank charges, family living costs, farm utilities (electricity, phone, etc.), fuel and lubricants (unallocated), full-time labour, licenses, management salary, other cash expenses, provincial government levy, repairs and maintenance (unallocated), short-term insurance and UIF
- The following **assets** of a typical Eastern Basin dryland farm were incorporated in the model framework, with asset replacements:
 - Debtors, equipment and tools, implements and machinery, land and fixed improvements, office equipment, other investments (shares etc.), production means, VAT receivable and vehicles
 - Assets are replaced according to an asset replacement strategy (e.g. vehicles every 5 years and implements and machinery every 7 years) when sufficient cash is available to purchase new equipment.
- Average long-term and medium-term **liabilities** of a typical Eastern Basin dryland farm were incorporated in the model framework.
- To model the impact that the use of treated mine water can have on a typical commercial farm in the Eastern Basin, the farm's overall structure had to be adjusted with the following assumed changes:
 - To intensify the farm and include 120 ha under irrigation, the following required equipment investments were assumed:
 - 3 x 40 ha Pivots
 - Pump house
 - Pipes
 - Fence and alarm system for security
 - ***It was assumed that the farmer does not pay for the CAPEX investment of the water infrastructure required to convey the water from the mine to the farm's point-of-supply.***
 - ***It was assumed that farmers could access water on demand, and no on-farm storage is required³. This can be feasible if there is adequate pumping and treatment capacity (if required), as well as the capacity to store or manage excess water. These implementation considerations are discussed in Chapter 5.***
 - A 10% deposit for the investment in the irrigation and safety equipment and infrastructure (mentioned above) is paid in the first year, and the rest is financed through a medium-term loan, subject to annual principal payments and interest. The total CAPEX investment cost was assumed to be R10.59 million (excluding interest).
 - Given these additional investments, the value of the land used for irrigation was increased.

³ In reality, a farm dam would typically mitigate water availability risk for the farmer, but this investment is seen as an optional "nice-to-have".

The following assumptions were made when modelling the scenario where mine water (treated or untreated) was used:

- The 120 ha irrigation area was reallocated from the 450 ha dryland area, thus keeping the total area that the farm cultivates constant at 450 ha. The remaining 330ha dryland area cultivated the same share of dryland maize, soybean and fallow land (thus the dryland area per crop decreased, but the share of dryland area per crop remained the same).
- The impact of the use of treated water was simulated by UP using the IrrigWQ DSS(du Plessis, et al., 2023). According to the results, only maize yields are negatively affected when treated water (-1.4%) or untreated water (-1.8%) is used.
- Three additional permanent workers were employed when intensifying the farm with crop production under irrigation.
- Producers will need to pay for water, as indicated in Table 4.4
- The mine waters are expected to acidify soil to varying degrees; therefore, lime was applied as indicated in Table 4.5 to mitigate these effects.
- The mine water is expected to be somewhat scaling over time. However, these effects were not accounted for in this study as previously discussed.

4.4 ANALYSIS OF ECONOMIC SUSTAINABILITY, SOCIOECONOMIC IMPACTS AND SCALABILITY OF MINE WATER IRRIGATION

To quantify the financial impact of investing in irrigation equipment to utilise the mine water (treated or untreated), the economic situation of the farm was modelled for 8 years (from 2023 to 2030), with the following versions of the same farm:

- **Base:** without the irrigation intensification (only cultivating dryland maize and soybeans on 450 ha)
- **Maximum Area Irrigated:** intensification of 120 ha under irrigation, with 120 ha **maize** and 40ha **oats, double-cropping:**
 - This scenario assumes that the area required to fully utilise the available water (110 ML/day) is calculated based on the season where the least amount of irrigation is required, i.e., the summer season. In this scenario, a large area will be planted in summer, and a smaller portion will be planted in winter.
- **Minimum Area Irrigated:** intensification of 120 ha under irrigation, with 120 ha **maize** and 120 ha **oats double-cropping**
 - This scenario assumes that the area required to fully utilise the available water (110 ML/day) is calculated based on the season where the largest amount of irrigation is required (winter). In this scenario, the area to be planted in summer will be less than the area required to utilise the available water (remaining at 120 ha), leaving excess water in the system. The assumption was made that the excess water not used can be discharged; thus, storage costs were excluded.

For the irrigation intensification farms, the model also considers the required investment cost to intensify 120 ha with irrigation, the cost of water, the additional labour cost, and the additional lime cost due to water quality affecting the soil.

The potential impact of using the treated or untreated mine water needed to be quantified. Hence, the minimum and maximum irrigation area farms were simulated with treated and untreated mine water. Thus, the following simulations were run to model the total farm impact:

1. Base – Dryland Cash Crops (excluding irrigation)
2. Irrigation Intensification with Maize/Oats rotation using **treated** mine water – **maximum** area irrigated
3. Irrigation Intensification with Maize/Oats rotation using **treated** mine water (**minimum** area irrigated)
4. Irrigation Intensification with Maize/Oats rotation using **untreated** mine water – **maximum** area irrigated

5. Irrigation Intensification with Maize/Oats rotation using **untreated** mine water (**minimum** area irrigated)

Figure 4.13 illustrates the net farm income for each of the simulated farms (as listed above), taking into account the gross margin of the crops produced on each of the farms, as well as the farm's overhead costs, assets and liabilities. Figure 4.14 illustrates the difference in total net farm income between the irrigation intensification farms and the dryland base farm.

Initially, the base farm performs better than the intensification farms due to the higher investment in irrigation facilities. Over time, the minimum-irrigation-area scenario performs better than the base farm. However, the **maximum irrigation area scenario continues to perform poorer than the base farm**. This is because only 40 additional hectares are added to the farm for winter crop production (to ensure there is sufficient water for the expanded area), which is insufficient additional income to cover the extra cost of repaying the irrigation investment.

This suggests that **farmers will need to double-crop for the investment in irrigation equipment to be economically sustainable, and cannot irrigate only in the summer** and leave the fields fallow in the winter. This is further supported by the fact that the dryland gross margins are higher than the irrigation gross margins per hectare, as illustrated in Figure 4.12.

However, **when looking at the overall farm cash flow, the base farm has a more positive net cash surplus than the mine water irrigated farms** (Figure 4.15), mainly driven by a high investment payback and depreciation. However, if the model is extended to 30 years (the typical lifetime of a pivot), the cash flow may be more beneficial for irrigation intensification scenarios in the future. Given these results, it may be favourable to conduct further research and expand the model to include more years up to the pivot's life end (30 years).

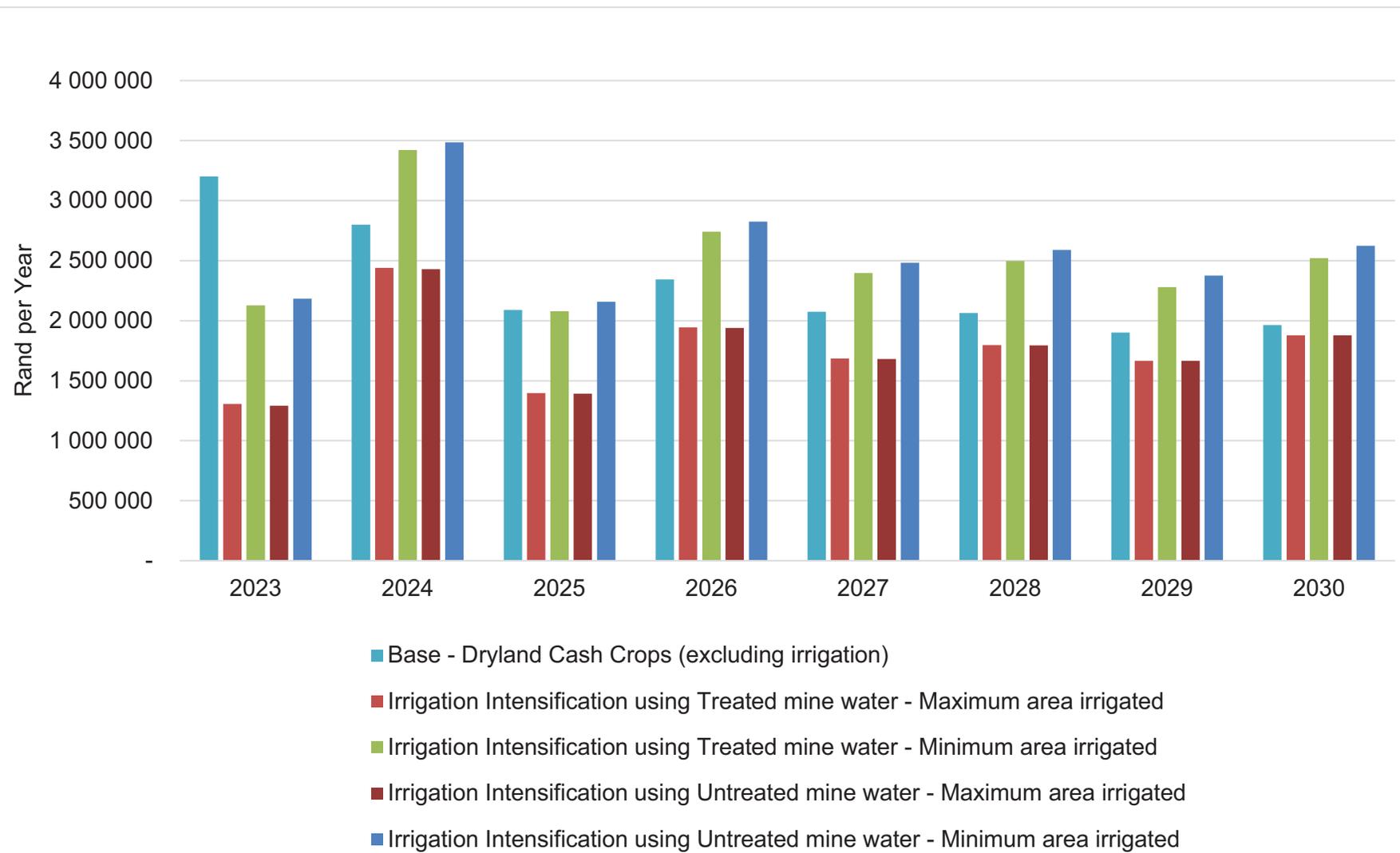


Figure 4.11 Net farm income per simulated farm

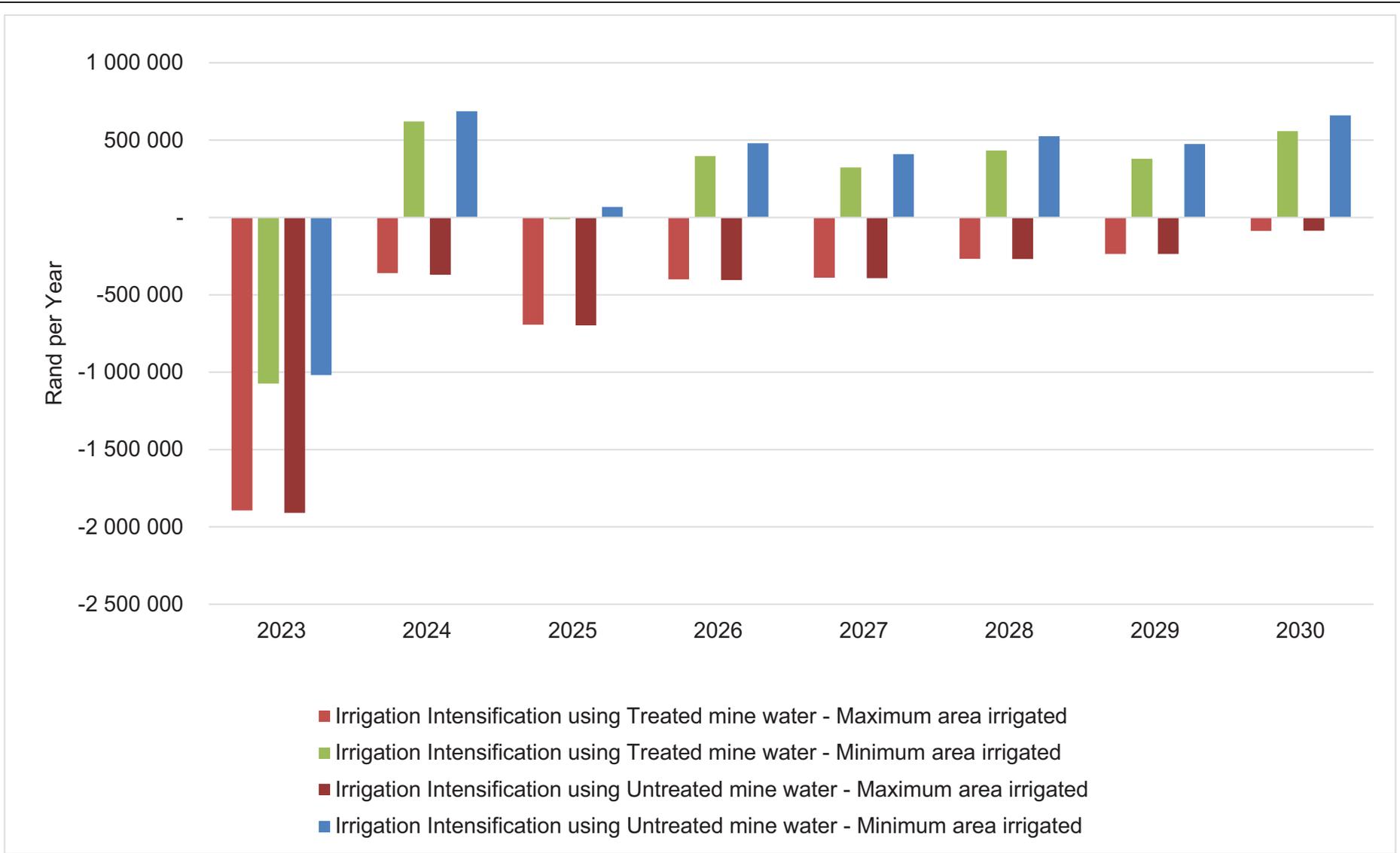


Figure 4.12 Difference in net farm income per simulated farm

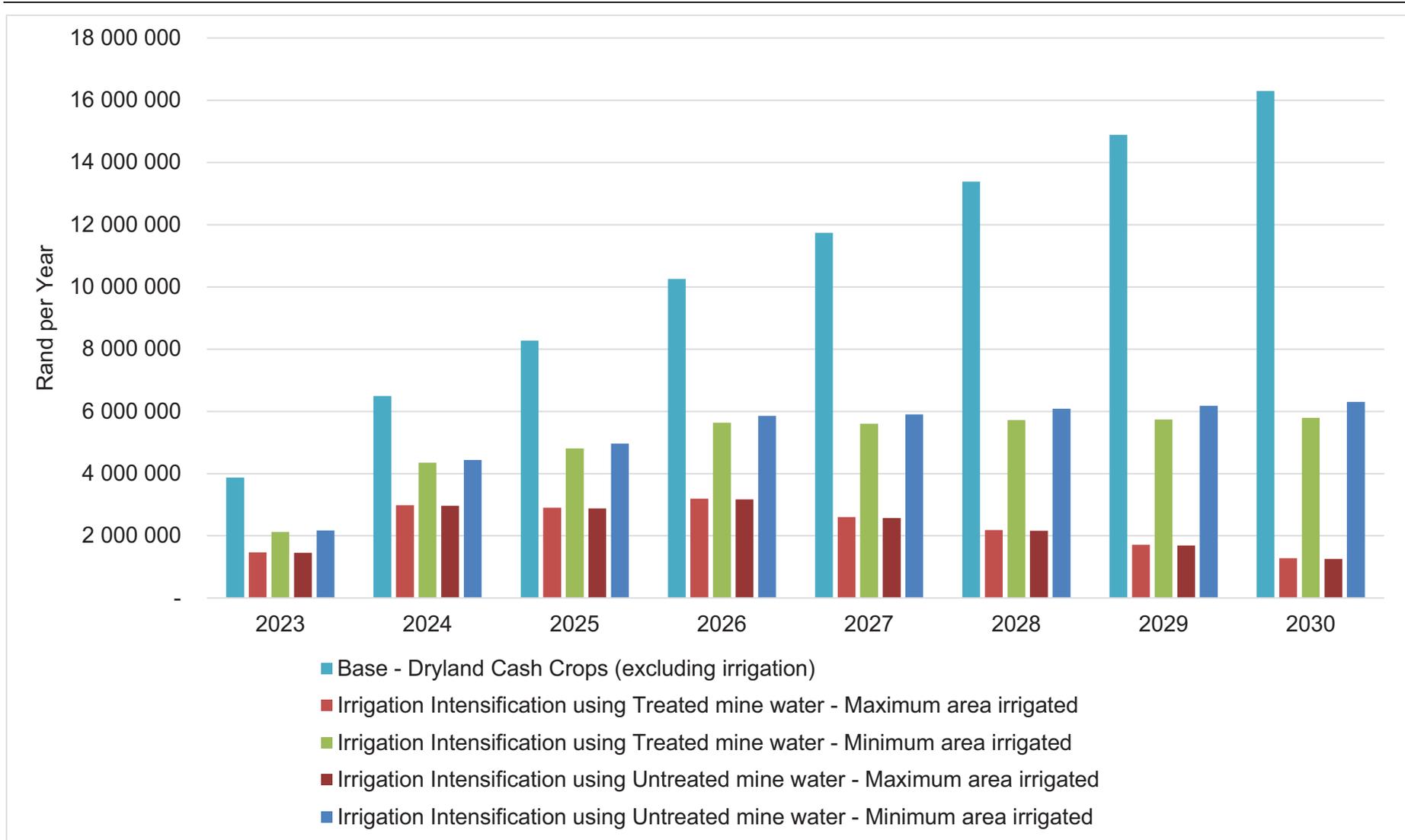


Figure 4.13 Total Farm Cashflow

4.4.1 Cost of water scenario

The cost of irrigation water that farmers pay plays a significant role in the feasibility of using it for crop production. Figure 4.16 illustrates the capital expenditure for the irrigation investment (deposit, payment, and interest), as well as the operational expenditure (water, electricity, scheduling, and repairs and maintenance) for planting under 120 ha of irrigation in summer and winter, summed over the simulated years (2023 to 2030). Capital investment expenditure is the chief cost component, followed by electricity operational costs and interest on the investment.

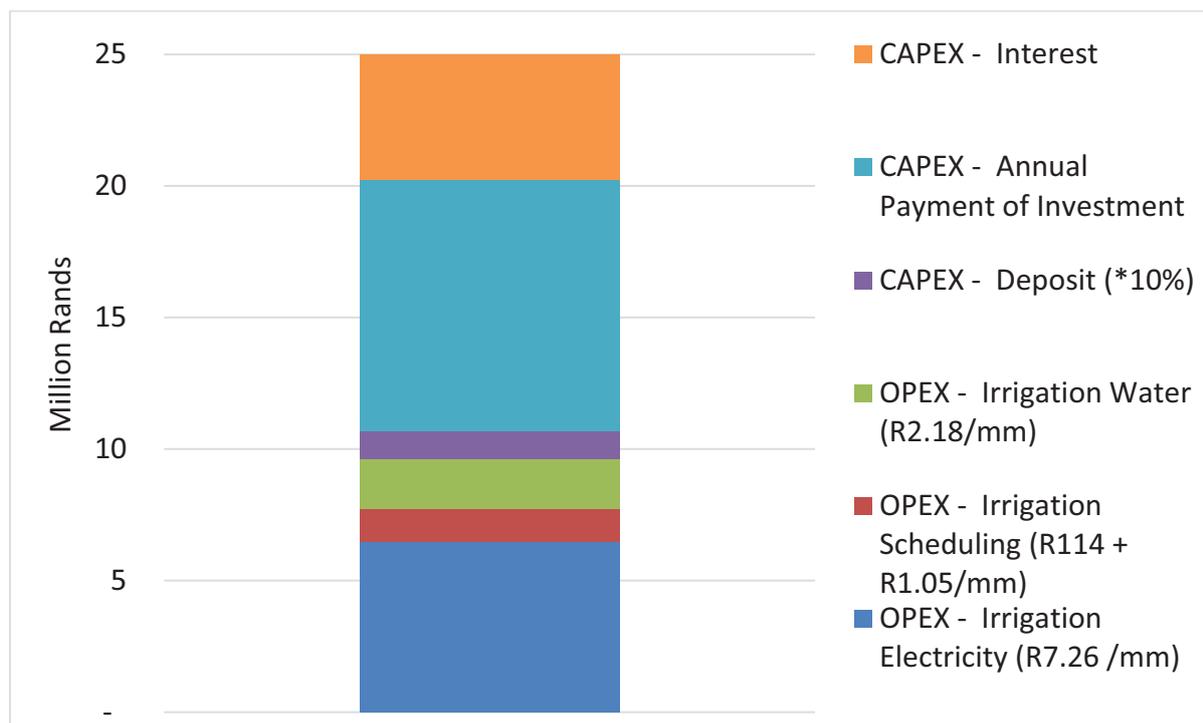


Figure 4.14 Total Cost of Irrigation (CAPEX and OPEX), the minimum area irrigated scenario, summed from 2023 to 2030

Figure 4.17 illustrates the total net farm income of a typical farm in the Eastern Basin summed from 2023 to 2030, under the base scenario (where all crops are produced on dryland), and for the most profitable intensification irrigation scenario (120 ha maize and 120 ha oats double-cropping (the minimum area irrigated scenario), with treated water), at different water cost levels. **The total net farm income over the eight years is higher for all tested sensitivities (20% above and below the current water price), except for R32.14/mm, when producers need to pay for the infrastructure.**

However, if farmers can only irrigate 120ha in the summer and 40ha in the winter (the maximum area irrigated scenario), Figure 4.18 illustrates that **even if the producers receive water at no cost (but still need to pay for electricity to pump the water to the field and for water scheduling for system management), the total net farm income over the eight years will still be below the base dryland scenario.** If farmers are expected to pay for the infrastructure investment cost (R30.98/mm), net farm income would be reduced by R20 million over the eight years. However, if producers need to pay for the infrastructure, the total net income under the minimum area irrigated scenario (Figure 4.17) is more negative than under the maximum area irrigation scenario (Figure 4.18), because more water is being used, and hence crops under irrigation have higher costs.

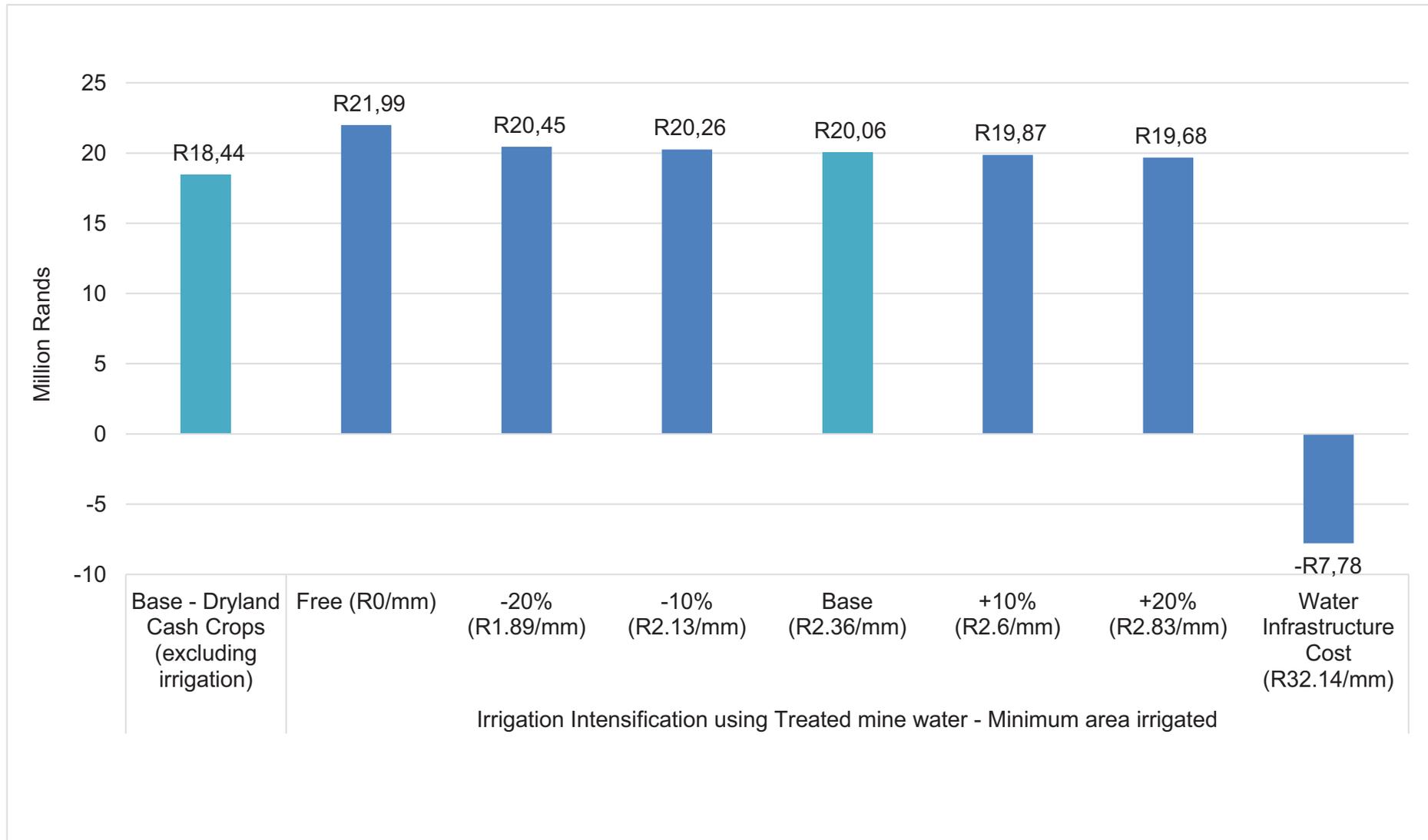


Figure 4.15 Sensitivity Analysis of Total Farm Net Income (2023 to 2030) of the minimum area irrigated scenario (120ha maize & 120ha oats), given different Water Cost Levels

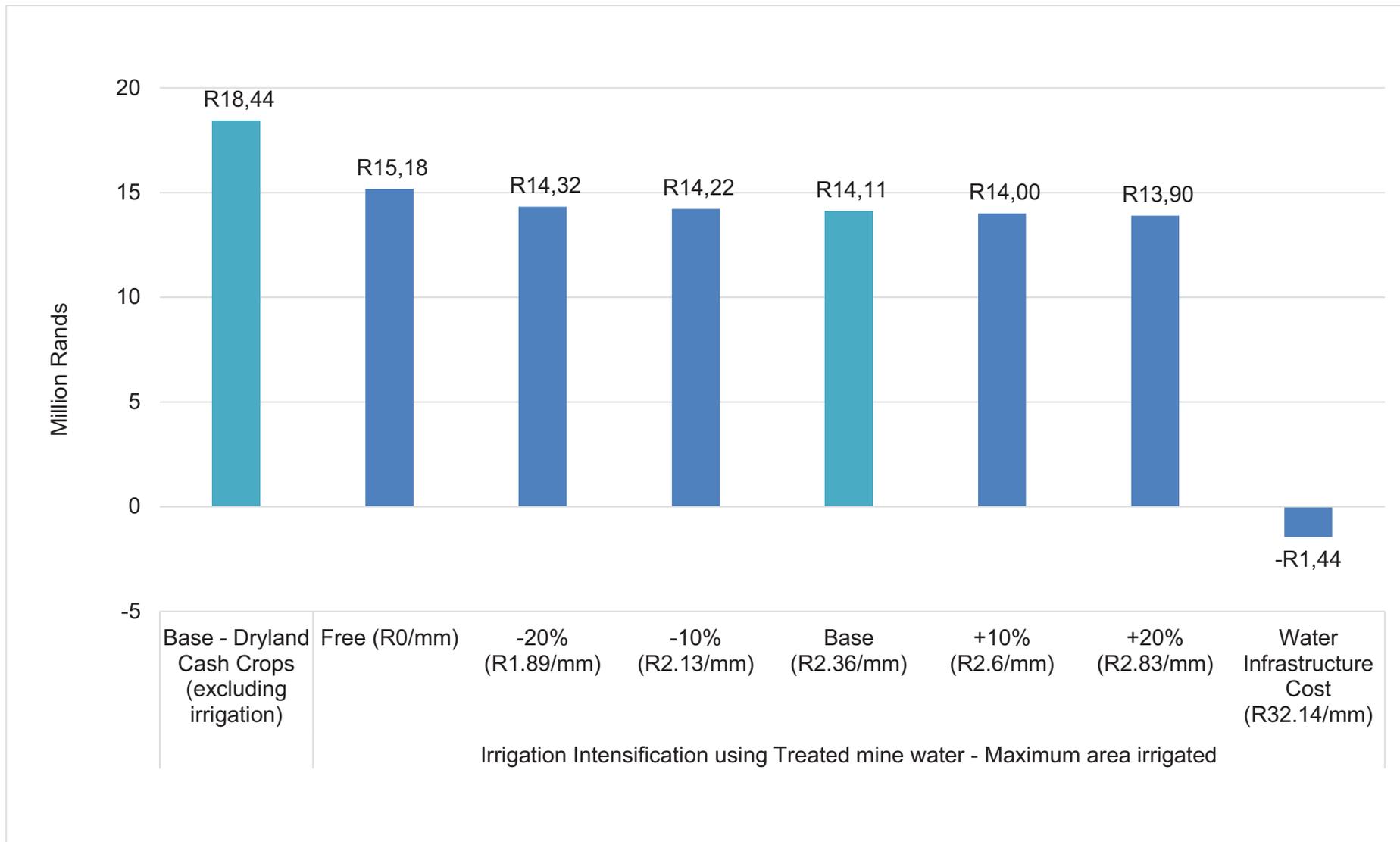


Figure 4.16 Sensitivity Analysis of Total Farm Net Income (2023 to 2030) of the maximum area irrigated scenario (120ha maize & 40ha oats), given different Water Cost Levels

4.4.2 Scalability quantification

Given the whole-farm model and the demonstrated economic sustainability of intensifying production on 120ha of its field crop area, this section aims to present the scaling of irrigation from the water treatment plant. Theoretically, defining the **possible irrigation area** will allow for the environmental impact assessment in a forthcoming output.

The crop rotation assumed for irrigation is maize in summer and oats in winter. Considering the daily treated water volume supplied by the treatment plant, maize and oats water requirements, and average rainfall and its timing in the area, the **total potential irrigation area can amount to 6100ha in summer and 2400ha in winter**. This section details the spatial allocation of this potential irrigation area.

The field crop boundaries within a 30km radius from the water treatment site include horticulture, pivot and non-pivot irrigation, old fields, rainfed annual crop cultivation and pastures, smallholdings, shade net and subsistence farming (DALRRD, 2021). In demonstrating where, spatially, fields could be irrigated with the treated mine water, possible new pivot irrigation fields were identified, i.e. the most suitable circular area of either 20 or 40 ha, which is currently utilised for annual dryland field crops or pasture. Furthermore, these areas should not fall within the no-go zones of dolomitic land, streams, or rivers, or have a 5-year contamination risk. Thus, although the total available agricultural use area is 84 240 ha, only 73 049 ha are annual dryland crops/pasture. Of this, due to no-go zones, only 42 411 ha are potentially available for irrigation.

3297 fields that meet the criteria were identified. However, only 219 fields are larger than 40ha, whereas 645 fields are larger than 20ha. Fields are, however, irregular in shape. Thus, not all fields can accommodate a 40 ha or 20 ha pivot as the circular shape of the pivot may extend beyond the field's boundaries.

The question of how many pivots (circles) fit into an irregularly shaped field (polygon) seems simple, but it requires a complex answer, as it is a bin-packing problem. All depends on how the pivots (circles) are orientated within the irregularly shaped field (polygon) of which there are a multitude of answers (heuristic problem).

The following algorithm steps were implemented (via ArcGIS and R), assuming that farmers are not likely to change physical field crop boundaries significantly from the currently defined field crop boundary database:

1. A 10m grid was defined within each field (10m raster),
2. The centre of each grid-block was determined (raster to point)
3. Then a 356.824823m or 252.313252m buffer was created around each point (the 356.824823m or 252.313252m is the radius of a circle with an area of 40 ha or 20 ha, respectively). Resulting in 40ha or 20ha circular potential field suggestions.
4. However, many of these circular buffers that represent a pivot exceed the field (polygon) boundaries. Using the select by location tool, only buffers (pivots/circles) that fall within a field were selected, resulting in a subset of pivot placement options per dryland field (all permutations that fit within the field boundaries).
5. Finally, an R code was implemented to select one or two pivots per original dryland field:
6. Determine the pair-wise distance matrix between all potential pivot centroids.
7. If the maximum distance is smaller than 2 x 356.824823 m (40ha set) or 252.313252 m (20ha set), select one pivot at random.
8. If the maximum distance exceeds 2x 356.824823 m (40ha set) or 252.313252 m (20ha set), select the two pivots that are maximum distance apart within the field.

9. The selected 20 ha and 40 ha pivots were combined into one shapefile representing the potential irrigation area.

The resulting potential irrigation area is summarised in Table 4.5 and illustrated in Figure 4.19. 90% (2160 ha) of the required 2400 ha irrigation area in the winter season falls within a 15 km radius of the treatment plant. While 50% (3000 ha) of the required 6100 ha falls within 20 km of the treatment plant, 50% is between 20 and 30 km from the treatment plant.

Table 4.6: Potential irrigation area breakdown

Distance from water treatment plant	Number of pivots (40 ha and 20 ha pivots)	Potential irrigation area (ha)
5 km	3	60
10 km	30	680
15 km	98	2160
20km	139	3000
30 km	293	6100

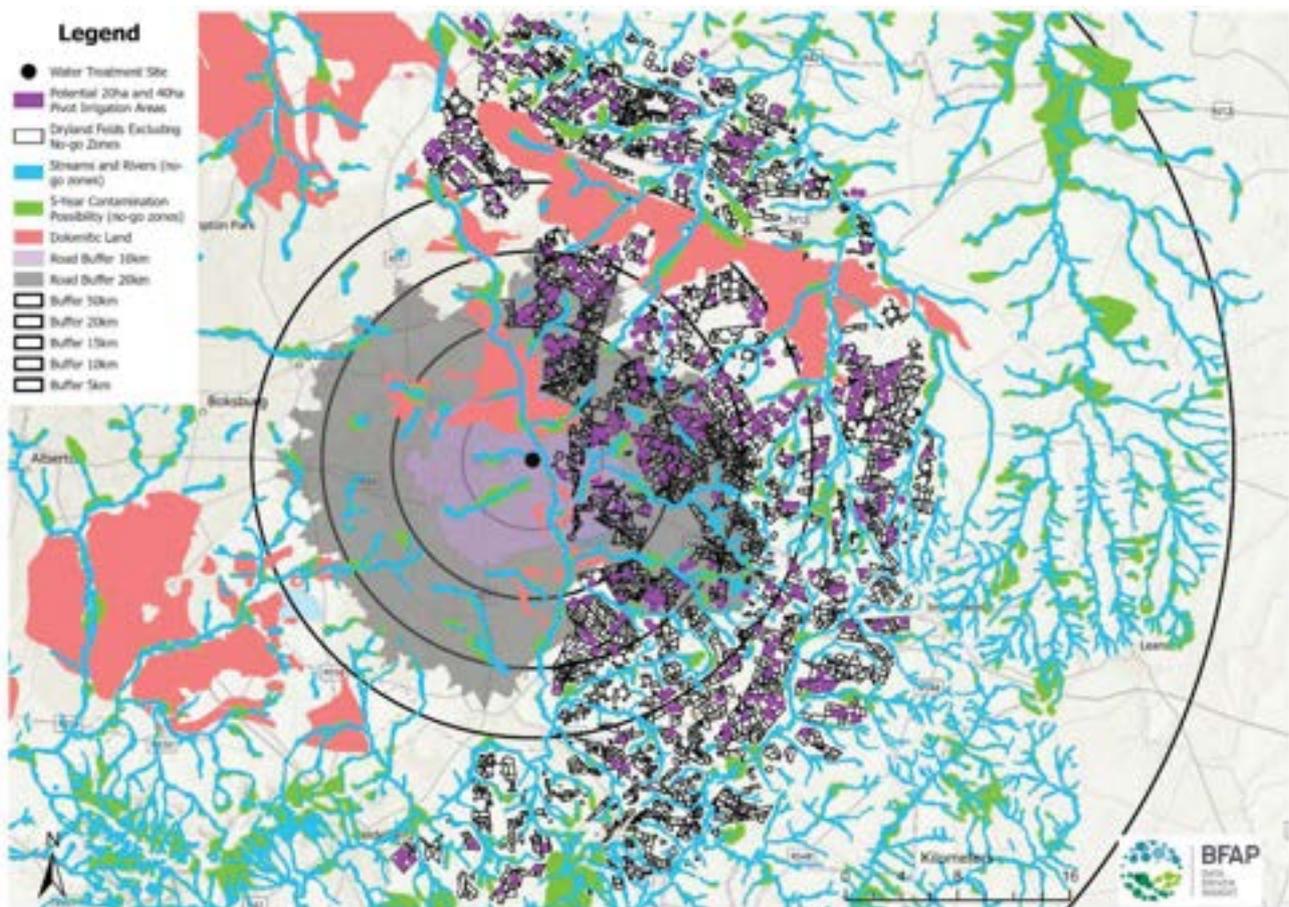


Figure 4.17: Potential irrigation area

4.4.3 Socioeconomic impact

From the socioeconomic considerations presented in Section 1.2, the key messages can be summarised as follows:

1) **Mostly built-up and highly populous area:**

- Ekurhuleni has the highest population density (1,609 persons/km²) and a significant poverty rate (27% of households earn below the upper-bound poverty line). With a large young population (ages 15-34) and a 21% unemployment rate, it represents a significant labour pool. This area also has many small animals (e.g., chickens), suggesting a demand for small-grain feed and easy access to an informal local market. Apart from being a labour pool, the importance of focusing on staple crops to strengthen the food security (access to affordable food) of the large number of low-income households is paramount. Irrigated agricultural production nearby has the potential to boost the local food supply.
- The City of Johannesburg and City of Tshwane, while sharing similarities with Ekurhuleni, are on the outskirts of the 50 km radius. Transport costs may reduce their market profitability compared to closer regions.

2) **Diversity in Economic Profiles and Potential Risks:**

- Victor Khanye has lower population density, fewer livestock, and lower poverty, making it less economically active compared to areas like Govan Mbeki, which has a larger population and significant livestock numbers. Govan Mbeki offers potential for animal feed markets, though informal grazing and theft pose risks to animal feed crops grown during periods of scarcity (e.g., oats in winter). Other municipalities, such as Victor Khanye and Midvaal, have lower livestock numbers, limiting the scope of the agricultural market.

3) **Income and Poverty Distribution:**

- The percentage of households below the lower- and upper-bound poverty lines varies, with incidences slightly lower in some areas like Midvaal (17% at LBPL) but higher in Ekurhuleni (22%). The distribution indicates varying degrees of economic need and market potential across municipalities.

4) **Employment and Dependency Ratios:**

- Unemployment rates vary from 14% in Midvaal to 26% in Dipaleseng. Dependency ratios are also higher in areas with higher poverty, which impacts labour availability and local market activity.

These findings can guide resource allocation and development planning by emphasising areas with a high potential labour pool (Ekurhuleni) and those offering informal markets for animal feed (Govan Mbeki), while considering transport and poverty constraints.

A total potential irrigation area of between 2400ha and 6100ha, divided among typical farms (as demonstrated in previous sections) that each convert 120ha of their cropland to pivot-irrigated fields, implies this opportunity is available to 20-50 farmers in the area.

The whole-farm model assumed that 3 additional permanent workers would be employed when intensifying the farm through irrigation-based crop production. This additional employment speaks to:

- Additional operations, as well as repairs and maintenance requirements on the irrigation infrastructure investment
- additional security
- harvesting and handling requirements of oats in particular.

Note that field crop labour multipliers (labourers employed per hectare of field crop production) are low and do not differ significantly between dryland and irrigated production. Given these assumptions, the employment impact of intensified field crop production in the area could range between 60 and 150 jobs. Given an average of 3 dependents, these jobs can impact the livelihoods of 120 – 450 people in the area surrounding the water treatment plant.

4.5 DISCUSSION

Investment in irrigation initially reduced farm profitability (net farm income) due to high upfront costs. However, over time, the minimum-area irrigated scenario (120ha double-cropping with maize and oats) outperforms the dryland base scenario, highlighting the potential long-term benefits of irrigation, provided double-cropping is used to maximise resource use. The maximum area irrigated scenario (120ha maize and 40ha oats) performed poorly relative to the base dryland farm due to the limited additional crop area. This setup resulted in insufficient income to justify the irrigation investment costs, suggesting that double-cropping is essential for financial sustainability in intensified irrigation models.

The cost of irrigation water and associated operational expenses, particularly electricity, significantly influenced profitability. Higher water costs reduced net income over the 8-year modelling period, with water, electricity, and investment interest accounting for the largest share of expenditure. Despite improved net farm income in the minimum-area-irrigated scenario, the base farm maintained a more positive cash flow over the 8-year model due to the absence of investment and depreciation costs. Extending the model to 30 years (matching the lifespan of irrigation pivots) could reveal more favourable cash flow outcomes for irrigation scenarios, highlighting the need for longer-term analysis.

The sensitivity analyses showed that, at current water prices, the minimum irrigation scenario yields positive income relative to the dryland base. However, at higher water costs, even this scenario becomes less viable. Thus, the cost of water will play a pivotal role in the economic sustainability of mine water irrigation. The maximum area scenario (120ha maize & 40ha oats) yielded lower net income than the base scenario, even at zero water cost, because operational expenses (such as electricity) still apply, and the area limitation reduced income potential. This outcome emphasises that maximising irrigation area (i.e., ensuring maximum mine water use) does not necessarily lead to on-farm financial gains without addressing the balance between cropping area and costs.

Spatial analyses indicated that the available land can accommodate 6000ha of irrigated cropping in addition to the existing irrigated area within a 30km radius of the water treatment plant. An area of 2400 ha can be allocated for summer and winter cropping, while an area of 3600 ha can be allocated for summer-only cropping. A combination of 20h and 40ha pivots can be accommodated within the identified areas. Assumptions about the crop to be irrigated, farmers' ability to change physical field boundaries, and water storage solutions will significantly impact both the potential irrigation area outcome and the spatially scaled irrigation outcome.

Ekurhuleni, with its high population density and poverty rate, represents a strong labour pool and potential market for staple crops to support food security. This municipality, along with others near the water treatment plant, could benefit from nearby irrigated agricultural production to improve livelihoods and the local food supply. Unemployment and dependency ratios vary across municipalities, ranging from 14% to 26%. This suggests that economic interventions, especially in job creation, could be tailored to areas with higher dependency and poverty rates to boost local economies. If 2,400 to 6,100 hectares are pivot-irrigated across 20 to 50 farms, this could intensify crop production on a typical 120ha per farm. This expansion would likely create 60 to 150 jobs, which could indirectly benefit 120 to 450 dependents in the community.

4.6 CONCLUSION

An economic model was developed to assess the economic sustainability, socioeconomic impacts and scalability of mine water irrigation. The economic assessments highlighted the potential long-term benefits of irrigation, provided double-cropping is used to maximise resource use. The results indicated that although irrigation intensification can be beneficial, its success depends on water cost management, optimised cropping strategies, and long-term investment perspectives. Spatial analyses showed that there is sufficient land to support 6000ha of additional irrigated crop production within a 30km radius of the EB treatment plant. It is expected that the irrigation intensification outputs generated by the whole-farm model will be scalable to 6000ha. Irrigation intensification is also likely to support livelihood creation. It is predicted that targeted agricultural investment and employment in the areas surrounding the water treatment plant could help food security, boost local economies, and improve the livelihoods of hundreds in these communities.

CHAPTER 5: KEY CONSIDERATIONS FOR LOCATING LARGE-SCALE MINE WATER IRRIGATION SCHEMES IN THE WITWATERSRAND GOLDFIELDS

Current and previous work undertaken has shown that mine water irrigated cropping systems can be flexible and require only that the main objective for establishing such systems be clearly defined, whether it be environmental protection by reducing salt loads to surface water resources, maximising water use, or socioeconomic benefits such as reduced treatment costs or increased agricultural production. One key issue with irrigation is that it is a consumptive use of water, so it is only an option if the water is not needed elsewhere. In this case, we determined that it accounted for a small fraction of domestic water use, suggesting that consumptive use could be considered.

The crop trials and modelling conducted in this study have demonstrated that irrigation with both treated and untreated mine-influenced waters is a viable option for mine water management in the Witwatersrand Goldfields of South Africa. With careful planning and management, large-scale mine water irrigation is expected to be productive and profitable with acceptable environmental impacts. This study has developed an approach to assess the site-specific feasibility of mine water irrigation schemes and to guide their rollout. This chapter discusses the key considerations for locating large-scale mine water irrigation schemes in the Witwatersrand Goldfields, using the Eastern Basin as a model site.

It should be noted that the subsection numbering in this chapter is not indicative of order of importance or the sequence in which the factors highlighted should be considered. These factors are interlinked and interdependent and should not be considered independently.

5.1 WATER QUALITY AND QUANTITY

Water quality affects crop productivity through salinity, pH, and specific-ion effects, such as Na, Cl, Al, and other trace-element toxicities. Water quality can also affect infrastructure lifespan through corrosion or scaling, and clogging of irrigation equipment, with financial implications. When assessing the feasibility of large-scale mine water irrigation schemes, reliable current and predicted water quality data are required. Based on the glasshouse pot trials conducted, both treated and untreated mine waters can be used for irrigation, provided irrigators commit to liming their soils. However, for mine water irrigation to be sustainable, the water quality should ideally not deteriorate over time. If the quality is expected or observed to deteriorate to levels unsuitable for irrigation, treatment will be required.

Given that irrigation is a consumptive use of water, it is only a mine water management option if there is a surplus of mining-influenced water, that is, a positive mine water balance. Water make, and its seasonality, determine how much irrigation is possible, with implications for the area that can be planted, cropping system choices, and water storage requirements. Large volumes of water generated at high rates will generally require larger irrigation areas to fully utilise the excess water. If there is surplus water in the system throughout the year, the selected cropping system should ideally include crops that grow actively year-round. As with water quality, reliable current and predicted water make data is required to ensure sustainable irrigation and to make provision for additional storage or management requirements.

5.2 CROPPING SYSTEM SELECTION

Cropping system selection affects productivity, water use, and water storage requirements, and has notable socioeconomic implications. Crops sensitive to mine water constituents, such as salinity, will have low productivity. If such crops are selected, additional inputs will be required to improve productivity, which entails costs and may have some environmental implications. For example, salt-sensitive crops will require greater leaching, which will increase pumping and soil amendment costs and result in less gypsum precipitation in the soil profile, thereby increasing solute loads to groundwater.

Crop water requirements, rainfall amount, and seasonal distribution will determine irrigation water use, with implications for land and storage requirements. For example, crops with low water requirements will require larger areas to utilise as much of the excess water as possible than crops with higher water requirements. Similarly, in a summer rainfall area, summer cropping systems will require larger areas than winter cropping systems due to rainfall, or its absence, in the field water balance. Furthermore, a monocrop cropping system will utilise less water annually than a double-cropping system.

From a socioeconomic perspective, cropping system selection affects profitability and potential for job creation, even when water quality is not a limiting factor. For example, mechanised crops will generate fewer jobs than labour-intensive crops, unless there is an extensive downstream value chain that creates employment opportunities. On the other hand, labour-intensive crops that are difficult to mechanise might have a greater socioeconomic impact than mechanised crops; however, they may not be as profitable, particularly if the crop is sensitive to the mine water constituents.

Although both treated and untreated mine waters are expected to be suitable for sustained irrigation, provided irrigators commit to liming their soil, there may be real or perceived concerns about the safety of consuming the produce. These concerns can be addressed by using mine waters to irrigate industrial crops that can be used to produce fibre or biofuel instead of food crops. However, this will have socioeconomic implications, such as the relative profitability of industrial crops compared to food crops, which may influence farmer willingness to use these waters.

5.3 TOTAL IRRIGATION AREA

The total irrigation area depends on several factors, including water make and its seasonality, land and storage availability, and cropping system water requirements. In the Witwatersrand region, the summer crop will have significantly lower irrigation water requirements than the winter crop due to summer rainfall; therefore, a larger area will be required in the summer than in the winter to utilise as much mine water as possible. In this study, two scenarios were considered for determining the total irrigation area for a double-cropping system:

- The “Maximum area” scenario, in which the total irrigation area required to maximise mine water use was determined based on summer crop irrigation requirements
- The “Minimum Area” in which the total irrigation area required to maximise mine water use was determined based on winter crop irrigation requirements

The total area that will be irrigated has both environmental and socioeconomic implications. For example, in a double-cropping system, if the Maximum area is established for irrigation, the available mine water would not be sufficient to meet winter crop requirements. Therefore, in this scenario, a smaller area would need to be planted in winter than in summer. Conversely, if the “Minimum” area is established for irrigation, the area planted in summer would not be sufficient to utilise the available water; therefore, the excess water would need to be managed. The maximum-area scenario is predicted to be less profitable, and the *in-situ* environmental impact footprint is expected to be greater than in the minimum-area scenario. However, the minimum area scenario is expected to offer fewer opportunities for job creation, may entail broader costs and/or environmental impacts due to the excess water that would need to be managed.

5.4 MANAGEMENT OF EXCESS MINE WATER

Although irrigation is a consumptive use of water, some excess mine water is expected to remain in the system, mainly due to seasonal variations in water balance and crop water requirements. For irrigation to be a sustainable mine water management strategy, a balance between water make and use should be maintained; therefore, excess mine water must be managed. Management options include storage or discharge, and management requirements will depend on whether treated or untreated water is used for irrigation.

Building storage infrastructure will entail costs and depend on the cropping system's water requirements. If the onus is placed on farmers to develop such infrastructure, it could substantially increase irrigation capital costs, making it financially unfeasible. If the storage capacity is sufficient, underground workings could be used as "storage". This option would be most compatible with a double-cropping system, where large volumes of water are pumped in winter to reduce them to levels low enough to allow an increase in summer without exceeding environmental critical levels (ECLs). Pumping capacity and, if treated water will be used, the HDS treatment plant's capacity will affect the feasibility of this option.

If permitted, excess mine water could be discharged into surface water courses during periods of high rainfall or when the water made exceeds the water use. If untreated water is used for irrigation, it may be necessary to treat the excess before discharge. However, this will depend on whether the treatment plant can be easily switched on and off and whether there is allowance to treat smaller volumes than the design capacity. The discharge option is expected to contribute far less salt to receiving water bodies than the current situation, in which such waters are released year-round, as less water will be discharged, and there will be substantial dilution.

5.5 INFRASTRUCTURE

Agriculture in the Witwatersrand Goldfields, more specifically the Eastern Basin, is dominated by rainfed crop production, and the establishment of large-scale mine water irrigation would require infrastructure to convey water to irrigators. The most cost-effective way to achieve this would be through open gravity-fed canals. This is an option if the mine water source is at a higher altitude than the irrigation area or if it can be cost-effectively pumped to an elevation that would facilitate release to existing surface water channels.

Receiving water under pressure will drastically reduce irrigation costs at the farm level, making mine water irrigation more economically viable. However, this will require large-diameter pipes, which will have some cost implications. It would be most convenient to lay pipelines along existing roads, given existing servitude zoning and the road reserves. However, given the distribution of available land, the reach of a single irrigation pipeline could be minimal. The service network can be distributed in various directions, which may require an extensive pipeline for bulk water supply. Infrastructure would also need to be developed within each irrigation unit, particularly when converting from dryland, as modelled in this study.

5.6 LAND AVAILABILITY AND OWNERSHIP

Land availability will influence the amount of water that can be utilised and dictate the total irrigation area that can be established. Several factors contribute to the total area of land available for irrigation, including the land's irrigability and land ownership. Not all arable land is irrigable. Even though desktop assessments may show large areas of cultivated land being available, when establishing mine water irrigation schemes, it is vital to assess the irrigability of that land. Land ownership is a potential limiting factor for establishing mine water irrigation schemes in the Witwatersrand Goldfields. More than enough land appears to be available, and with the budgets looking favourable, enough farmers will likely be interested in using these waters, as long as the water costs are not too high.

5.7 WATER COSTING

The cost of water will play a pivotal role in the sustainability of mine water irrigation. Even in the most profitable scenario, where total irrigation area is allocated to maximise water use based on winter crop water requirements, mine water irrigation becomes unviable if irrigators have to pay for the bulk water conveyance infrastructure (i.e., off-farm infrastructure). The most profitable scenario for producers is one in which the irrigators receive treated water for free, and profitability decreases as water costs rise. If irrigation with untreated mine water is chosen and growers strategically lime their fields, the cost savings to government/taxpayers will be clear. There are many ways to approach such an irrigation rollout, and in-depth, site-specific studies will be required to develop optimal solutions.

5.8 SITING OF IRRIGATION SCHEMES

The siting of mine water irrigation fields has implications for the environmental impacts. It is crucial to avoid “no-go” areas, such as those underlain by dolomite or within proximity to surface water courses. However, this may reduce the total irrigable area. Fields located farther from such areas will have less impact. The spatial distribution and arrangement of the mine-water-irrigated fields will also influence the degree and extent of the environmental impact. Fields that are dispersed across the total available area will have less of an effect than fields that are concentrated within a smaller portion of the total available area. However, the feasibility of having a dispersed configuration will depend on land ownership and the total available land and will affect infrastructure costs.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Irrigation offers a cost-effective mine-water management option that supports water security and can create livelihoods. However, when irrigation was proposed as a mine water management option in the Witwatersrand Goldfields, the following concerns were raised:

- Are these waters suitable for sustained irrigation?
- What would the environmental impact be?
- Is sufficient irrigable land available in the built-up Witwatersrand region?
- Will farmers be willing to irrigate with these waters?
- What are the costs/benefits of this option?

The assessments conducted to address these concerns, along with the conclusions that can be drawn from them, are discussed below using the Eastern Basin as the model.

Are these waters suitable for sustained irrigation?

The glasshouse pot trials demonstrated that crops that are safe for consumption can successfully be produced with treated mine water from the Witwatersrand Goldfields. Furthermore, the untreated mine water from these goldfields can be utilised for irrigation if the soils are strategically limed. Crops irrigated with HDS-treated mine waters are expected to be safe for consumption. However, this needs to be verified with certainty and requires commodity-specific threshold values and reliable analyses.

Although the glasshouse pot trials have demonstrated that irrigation with mine water is agronomically feasible, establishing a long-term, commercial-scale mine water irrigation site in the Witwatersrand Goldfields would be highly beneficial. Such a site would be valuable for demonstrating the productivity and sustainability of large-scale irrigation with mine waters emanating from this region.

What would the environmental impact be?

Considering a conservative approach that assumes no retardation within the aquifer, it is predicted that return flow plumes do not reach surface water courses until 10 years of irrigation. However, the proportion of pivots with plumes reaching watercourses is expected to be low (<5%). After 25 years of irrigation, only 20% of the pivot return flow plumes are expected to reach surface water courses, and the amount doubles after 50 years (40-47%). These results suggest that although some impact is anticipated from large-scale irrigation with mine waters in the Eastern Basin, this practice can be sustainable in the medium- to long-term.

Irrigation return flow plumes that reach surface water bodies in a concentrated irrigation scenario are predicted to be proportionally greater than those in a dispersed irrigation scenario and to have higher solute concentrations. Additionally, focused pivots are expected to have a greater influence on the groundwater quality of the shallower weathered aquifer than dispersed irrigation pivots, due to the convergence of neighbouring plumes.

Overall, summer-only irrigated areas are expected to have a lower direct impact on the quality of surface and groundwater resources than areas irrigated in both summer and winter. However, if irrigation is applied only in summer, excess water would need to be managed in winter, and the impacts of this management would need to be quantified.

Irrigation should be considered as a long-term mine water management option in the Witwatersrand Goldfields. To facilitate responsible irrigation with mine water and protect groundwater resources, a site-specific monitoring programme and resource-quality objectives need to be in place and regulated, as specified in a WUL. Learnings from the commercial-scale mine water irrigation demonstration site established in the Mpumalanga Coalfields can be transferred to the goldfields.

What are the costs/benefits of this option?

The economic model showed that investment in irrigation will initially reduce farm profitability (net farm income) due to high capital costs. However, in the long term, irrigation with mine waters is expected to be profitable. The cost of irrigation water and associated operational expenses significantly influence profitability. High water prices will negatively impact the economic viability of mine water irrigation schemes. Considering the two scenarios (2400-6000 ha), 20-50 farms could be intensified with mine water irrigation in the Eastern Basin, creating at least 3 jobs per farm. Establishing emerging commercial farmers is likely to have a greater socioeconomic impact. However, land ownership is a potential limiting factor.

For mine water irrigation to be financially viable, the irrigation costs need to be low. Ideally, the mine water should be provided at no cost to the producer or at a discounted rate of the current water cost. There are many ways to approach such an irrigation rollout, and in-depth, site-specific studies will be required to develop optimal solutions.

Is sufficient irrigable land available in the built-up Witwatersrand region?

Spatial analyses indicated there is sufficient land available within a 30 km radius of the Eastern Basin AMD Treatment Plant to accommodate the establishment of up to 6000 ha of centre. The total area to be established will depend on the main irrigation priorities for mine water. However, land ownership is a potential limiting factor.

RECOMMENDATIONS

Although this study was extensive and successfully addressed all the aims set out, several limitations were identified that could not be addressed within the scope and timeframe allocated. The following research is therefore recommended to address these limitations:

- Understanding the hydrogeology of the underground mine workings in relation to storage capacity, uncontrolled mine water discharge points and quantifying the assimilative capacity of aquifers and receiving surface water bodies
- A detailed engineering study on water storage and conveyance, as well as the associated infrastructure costs and risks
- Field trials to validate the pot trial results and further investigate crop responses to sustained irrigation with this water, the consumption safety of produce, and the effects on soil quality over time.

REFERENCES

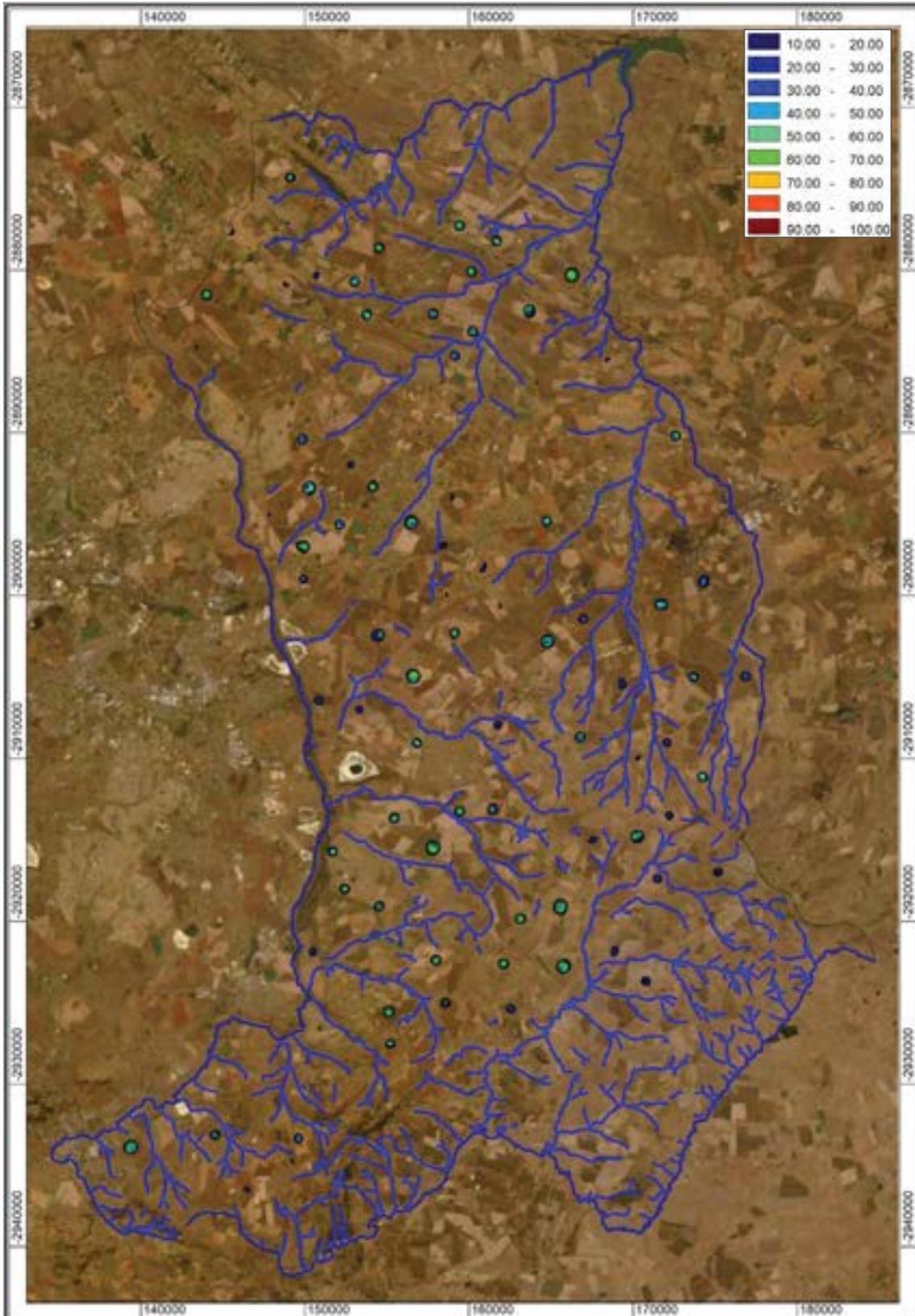
- AKCIL A and KOLDAS S (2006) Acid Mine Drainage (AMD): causes, treatment and case studies. *Journal of Cleaner Production* 14(12) 1139-1145.
- ALLINSON DW and DZIALO C (1981) The influence of lead, cadmium, and nickel on the growth of ryegrass and oats. *Plant and Soil* 62(1) 81-89. <https://doi.org/10.1007/bf02205027>.
- ANNANDALE J, BENADÉ N, JOVANOVIĆ N, STEYN J and DU SAUTOY N. (1999). Facilitating Irrigation Scheduling by Means of the Soil-Water Balance Model. (753/1/99). Pretoria: Water Research Commission.
- ANNANDALE J, DU PLESSIS M, TANNER P, HEUER S and MADISENG L (2023) Irrigation Should be Explored as a Sustainable Management Solution to the Acid Mine Drainage Legacy of the Witwatersrand Goldfields. *Mine Water and the Environment*. <https://doi.org/10.1007/s10230-023-00961-3>.
- ANNANDALE J, JOVANOVIĆ N, HODGSON F, USHER B, AKEN M, VAN DER WESTHUIZEN A, BRISTOW K and STEYN J (2006) Prediction of the environmental impact and sustainability of large-scale irrigation with gypsiferous mine-water on groundwater resources. *Water SA* 32(1). <https://doi.org/10.4314/wsa.v32i1.5235>.
- ANNANDALE J, JOVANOVIĆ N, PRETORIUS J, LORENTZ S, RETHMAN N and TANNER P (2001) Gypsiferous mine water use in irrigation on rehabilitated open-cast mine land: Crop Production, soil water and salt balance. *Ecological Engineering* 17(2-3) 153-164. [https://doi.org/10.1016/s0925-8574\(00\)00155-5](https://doi.org/10.1016/s0925-8574(00)00155-5).
- ANNANDALE J, STIRZAKER R, SINGELS A, VAN DER LAAN M and LAKER M (2011) Irrigation scheduling research: South African experiences and future prospects. *Water SA* 37(5). <https://doi.org/10.4314/wsa.v37i5.12>.
- ASHRAF M and MCNEILLY T (2004) Salinity tolerance in Brassica oilseeds. *Critical reviews in plant Sciences* 23(2) 157-174.
- BAHIZIRE F (2007) Effect of salinity on germination and seedling of canola (*Brassica napus* L.). Thesis (MScAgric Agronomy–University of Stellenbosch).
- BALOYI J, RAMDHANI N, MBHELE R and SIMATE GS (2024) Acid Mine Drainage from Gold Mining in South Africa: Remediation, Reuse, and Resource Recovery. *Mine Water and the Environment* 43(3) 418-430. <https://doi.org/10.1007/s10230-024-00994-2>.
- BI X, FENG X, YANG Y, LI X, SHIN GPY, LI F, QIU G, LI G, LIU T and FU Z (2009) Allocation and source attribution of lead and cadmium in maize (*Zea mays* L.) impacted by smelting emissions. *Environmental Pollution* 157(3) 834-839. <https://doi.org/https://doi.org/10.1016/j.envpol.2008.11.013>.
- COETZEE H HP, BURGESS J, THOMAS A, KEET MM (2010) Mine water management in the Witwatersrand Gold Fields with special emphasis on acid mine drainage.,
Department of Statistics South Africa(STATSSA)(2016) Community Survey 2016.
Department of Statistics South Africa (STATSSA)(2011) Census 2011.
- DEPARTMENT OF WATER AFFAIRS (SOUTH AFRICA)(DWA). (2013). Feasibility Study for a Long-Term Solution to address the Acid Mine Drainage associated with the East, Central and West Rand underground mining basins. Study Report No. 5.2: Assessment of the Water Quantity and Quality of the Witwatersrand Mine Voids - DWA Report No.: P RSA 000/00/16512/2.
- DEPARTMENT OF WATER AFFAIRS (SOUTH AFRICA)(DWS). (2018). Government Gazette No 42127, Proposed reserve determination of water resources for the Vaal catchment. National Water Act, 1998 (Act No. 36 of 1998),.
- DEPARTMENT OF WATER AFFAIRS AND FORESTRY (SOUTH AFRICA)(DWAf). (1996b). Volume 4: Agricultural Use: Irrigation. Department of Water Affairs and Forestry Pretoria, South Africa.
- DU PLESSIS M, ANNANDALE J, BENADÉ N, VAN DER LAAN M, JOOSTE HS, DU PREEZ C, BARNARD J, RODDA N, DABROWSKI JM and GENTHE B (2017) Risk Based, Site-specific, Irrigation Water Quality Guidelines: Description of decision support system, Water Research Commission, pp.

-
- DU PLESSIS MH, ANNANDALE JG and BENADÉ N (2023) A Decision Support System That Considers Risk and Site Specificity in the Assessment of Irrigation Water Quality (IrrigWQ). *Applied Sciences* 13(23) 12625. <https://doi.org/10.3390/app132312625>.
- ERIKSSON PG, ALTERMANN, W. AND HARTZER, F.J. (2006) The Transvaal Supergroup and its Precursors. In: MR JOHNSON, ANHAEUSSER, C. R. AND THOMAS, R. J. (ed), *The Geology of South Africa*. Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria.
- FAO-WHO(FAO-WHO). (2023). Joint FAO/WHO Food Standards Programme Codex Committee on Contaminants in Food (2023).
- FAO-WHO(FAO-WHO). (2023). Joint FAO/WHO Food Standards Programme Codex Committee on Contaminants in Food (2023).
- FERTILIZER SOCIETY OF SOUTH AFRICA(FSSA). (2000). Fertilizer handbook. (ISBN 0-909071-82-9). Pretoria, South Africa.
- GROUNDWATER SQUARE(2018) Gold One International – Modder East Mine: Groundwater Model Update, Drilling of Deep Monitoring Boreholes and Recommendations from Water Monitoring Report. Compiled for Gold One Modder East Operations. 2018. Contract No.: Reference:018e.
- GU J, ZOU G, SU S, LI S, LIU W, ZHAO H, LIU L, JIN L, TIAN Y, ZHANG X, WANG Y, ZHAO T, DU L and WEI D (2022) Effects of pH on Available Cadmium in Calcareous Soils and Culture Substrates. *Eurasian Soil Science* 55(12) 1714-1719. <https://doi.org/10.1134/s1064229322601391>.
- HEUER S, ANNANDALE J, TANNER P and DU PLESSIS H(2021) Technical Guidelines for Irrigation with Mine-Affected Waters. Pretoria: Water Research Commission; 2021. Report No.: TT 855/2/21. <https://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/TT%20855-2-21%20final%20web.pdf>.
- Johnson, M.R., van Vuuren, C.J., Visser, J.N.J., Cole, D.I., de V. Wickens, H., Christie, A.D.M., Roberts, D.L. and Brandl, G. 2006. Sedimentary Rocks of the Karoo Supergroup. In: Johnson, M.R., Anhaeusser, C. R. and Thomas, R. J. (Eds.). *The Geology of South Africa*. Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria. pp. 461-500.
- JOVANOVIĆ N, ANNANDALE J, CLAASSENS A, LORENTZ S, TANNER P, AKEN M and HODGSON F(2002) The influence of irrigation with gypsiferous mine water on soil properties and drainage water. Water Research Commission; 2002. Contract No.: 858/1/02.
- KISSEL DE, ISAAC RA, HITCHCOCK R, SONON LS and VENDRELL PF (2007) Implementation of Soil Lime Requirement by a Single-Addition Titration Method. *Communications in Soil Science and Plant Analysis* 38(9-10) 1341-1352. <https://doi.org/10.1080/00103620701328735>.
- KRONZUCKER HJ, COSKUN D, SCHULZE LM, WONG JR and BRITTO DT (2013) Sodium as nutrient and toxicant. *Plant and Soil* 369(1-2) 1-23. <https://doi.org/10.1007/s11104-013-1801-2>.
- MAAS EV and HOFFMAN GJ (1977) Crop salt tolerance—current assessment. *Journal of the irrigation and drainage division* 103(2) 115-134.
- MC CARTHY (2006) The Witwatersrand Supergroup. In: MR JOHNSON, ANHAEUSSER, C. R. AND THOMAS, R. J. (ed), Geological Society of South Africa, Johannesburg/Council for Geoscience.
- MEIMAROGLOU N and MOUZAKIS C (2025) Evaluation of the effects of intrinsic soil calcium carbonate and iron oxides on the properties of earthen building materials by means of engineered soils. *Low-carbon Materials and Green Construction* 3(1). <https://doi.org/10.1007/s44242-025-00066-w>.
- PRATT PF and SUAREZ DL (1990) Irrigation water quality assessments. ASCE, NEW YORK, NY,(USA), 1990. 220-236.
- RHOADES J (Year) Reclamation and management of salt affected soil after drainage. In: Proc. of 1st Annual Western Provincial Conf. Rationalization of Water and Soil Research and Management. Lightbridge, Alberta Canada, 1982, Session.
- ROBBINS CW (1991) Solute transport and reactions in salt-affected soils.
- ROSAS-CASTOR JM, GUZMÁN-MAR JL, HERNÁNDEZ-RAMÍREZ A, GARZA-GONZÁLEZ MT and HINOJOSA-REYES L (2014) Arsenic accumulation in maize crop (*Zea mays*): A review. *Science of The Total Environment* 488-489 176-187. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2014.04.075>.
-

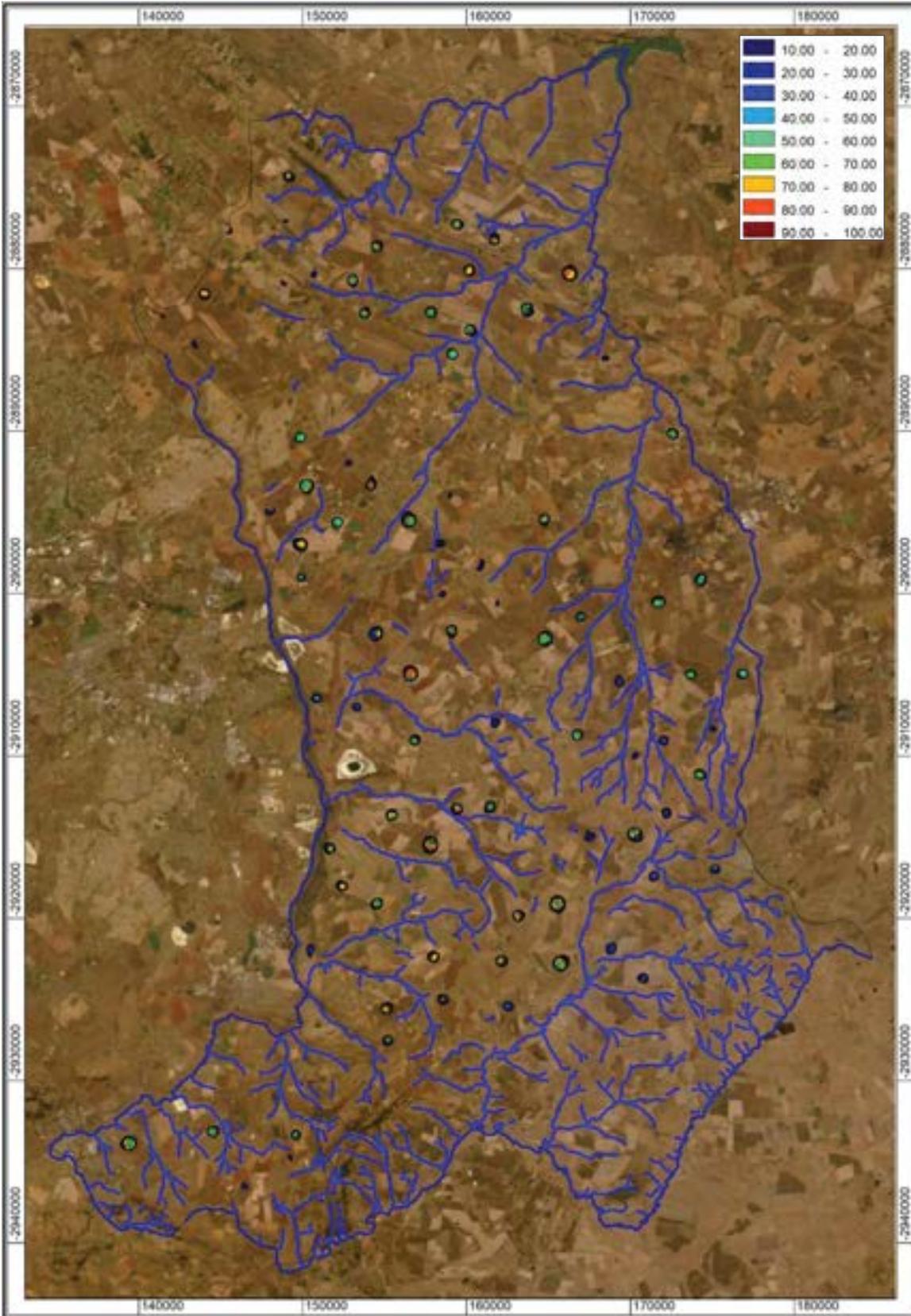
-
- SA DEPARTMENT OF AGRICULTURE FORESTRY AND FISHERIES(DAFF). (2012). Fertilizers, Farm Feeds, Agricultural Remedies And Stock Remedies Act, 1947 (Act No. 36 Of 1947).
- SA DEPARTMENT OF AGRICULTURE FORESTRY AND FISHERIES(DAFF). (2012). Fertilizers, Farm Feeds, Agricultural Remedies And Stock Remedies Act, 1947 (Act No. 36 Of 1947).
- SA DEPARTMENT OF WATER AFFAIRS AND FORESTRY(DWAF). (1996a). South African Water Quality Guidelines (second edition). South African Water Quality Guidelines – Volume 1: Domestic Use.
- SANTIAGO-ROSARIO LY, HARMS KE, ELDERD BD, HART PB and DASSANAYAKE M (2021) No escape: The influence of substrate sodium on plant growth and tissue sodium responses. *Ecology and Evolution* 11(20) 14231-14249. <https://doi.org/10.1002/ece3.8138>.
- SANTIAGO-ROSARIO LY, HARMS KE, ELDERD BD, HART PB and DASSANAYAKE M (2021) No escape: The influence of substrate sodium on plant growth and tissue sodium responses. *Ecology and Evolution* 11(20) 14231-14249. <https://doi.org/10.1002/ece3.8138>.
- SHRESTHA R, XUE Q, LEIVA SOTO A, GANJEGUNTE G, PALMATE SS, CHAGANTI V, KUMAR S, ULERY A, FLYNN R and ZAPATA S (2025) Seedling emergence in winter and spring canola genotypes under salinity stress. *Crop Science* 65(2) e70011.
- SIMATE GS and NDLOVU S (2014) Acid mine drainage: Challenges and opportunities. *Journal of Environmental Chemical Engineering* 2(3) 1785-1803.
- SINGELS A, ANNANDALE JG, DE JAGER J, SCHULZE RE, INMAN-BAMBER N, DURAND W, VAN RENSBURG L, VAN HEERDEN PS, CROSBY CT and GREEN GC (2010) Modelling crop growth and crop water relations in South Africa: Past achievements and lessons for the future. *South African Journal of Plant and Soil* 27(1) 49-65.
- TANHUANPää P, KALENDAR R, SCHULMAN AH and KIVIHARJU E (2007) A major gene for grain cadmium accumulation in oat (<i>Avena sativa</i> L.). *Genome* 50(6) 588-594. <https://doi.org/10.1139/g07-036>.
- VAN DER LAAN M, FEY MV, VAN DER BURGH G, DE JAGER PC, ANNANDALE JG and DU PLESSIS HM (2014) Feasibility study on the use of irrigation as part of a long-term acid mine water management strategy in the Vaal Basin. Research Report; 2014. Report No.: 2233/1/14. <https://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/2233-1-14.pdf>.
- WORLD HEALTH ORGANISATION(WHO). (2001). Depleted uranium: Sources, Exposure and Health Effects.
- ZHOU H-Y, NIAN F-Z, CHEN B-D, ZHU Y-G, YUE X-R, ZHANG N-M and XIA Y-S (2023) Synergistic Reduction of Arsenic Uptake and Alleviation of Leaf Arsenic Toxicity in Maize (*Zea mays* L.) by Arbuscular Mycorrhizal Fungi (AMF) and Exogenous Iron through Antioxidant Activity. *Journal of Fungi* 9(6) 677. <https://doi.org/10.3390/jof9060677>.
- ZHUANG Z, NIÑO-SAVALA AG, MI Z-D, WAN Y-N, SU D-C, LI H-F and FANGMEIER A (2021/04/15) Cadmium accumulation in wheat and maize grains from China: Interaction of soil properties, novel enrichment models and soil thresholds. *Environmental Pollution* 275. <https://doi.org/10.1016/j.envpol.2021.116623>.

APPENDIX A: RETURN FLOW PLUMES

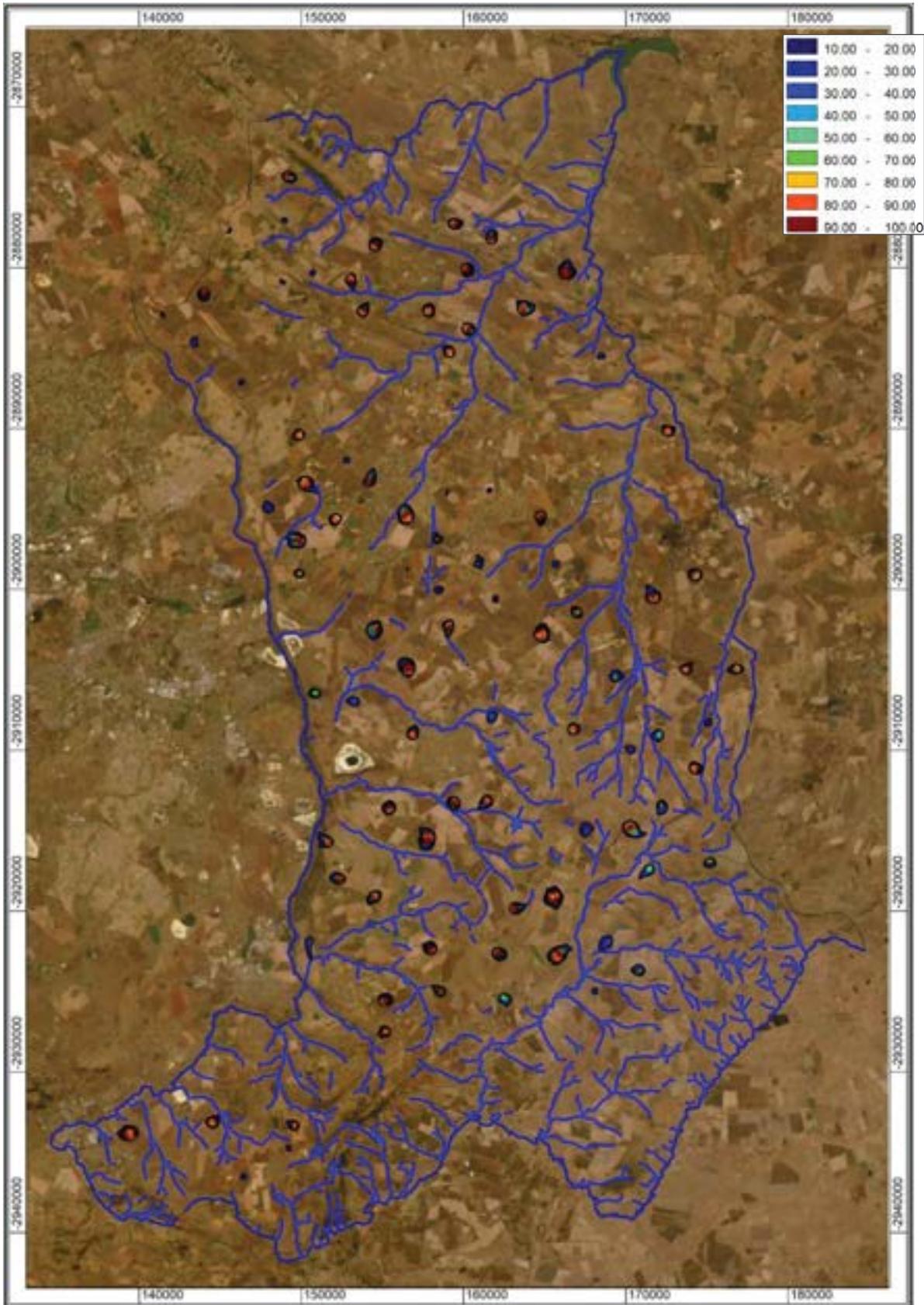
A1-Irrigation Return Flow Plumes after 5 years for the 2 400 ha Scenario with Dispersed Irrigation Pivots.



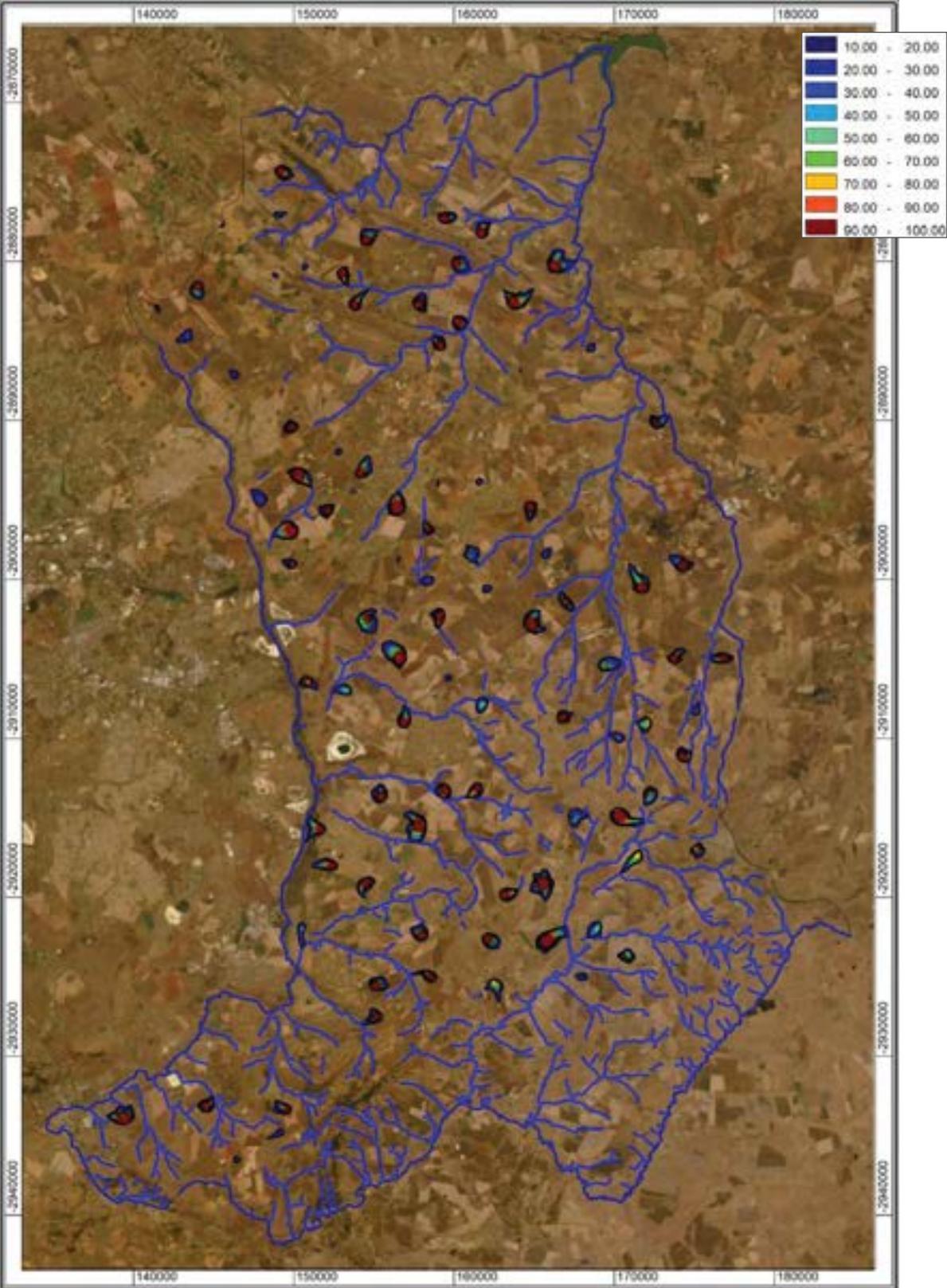
A2- Irrigation Return Flow Plumes after 10 years for the 2 400 ha Scenario with Dispersed Irrigation Pivots.



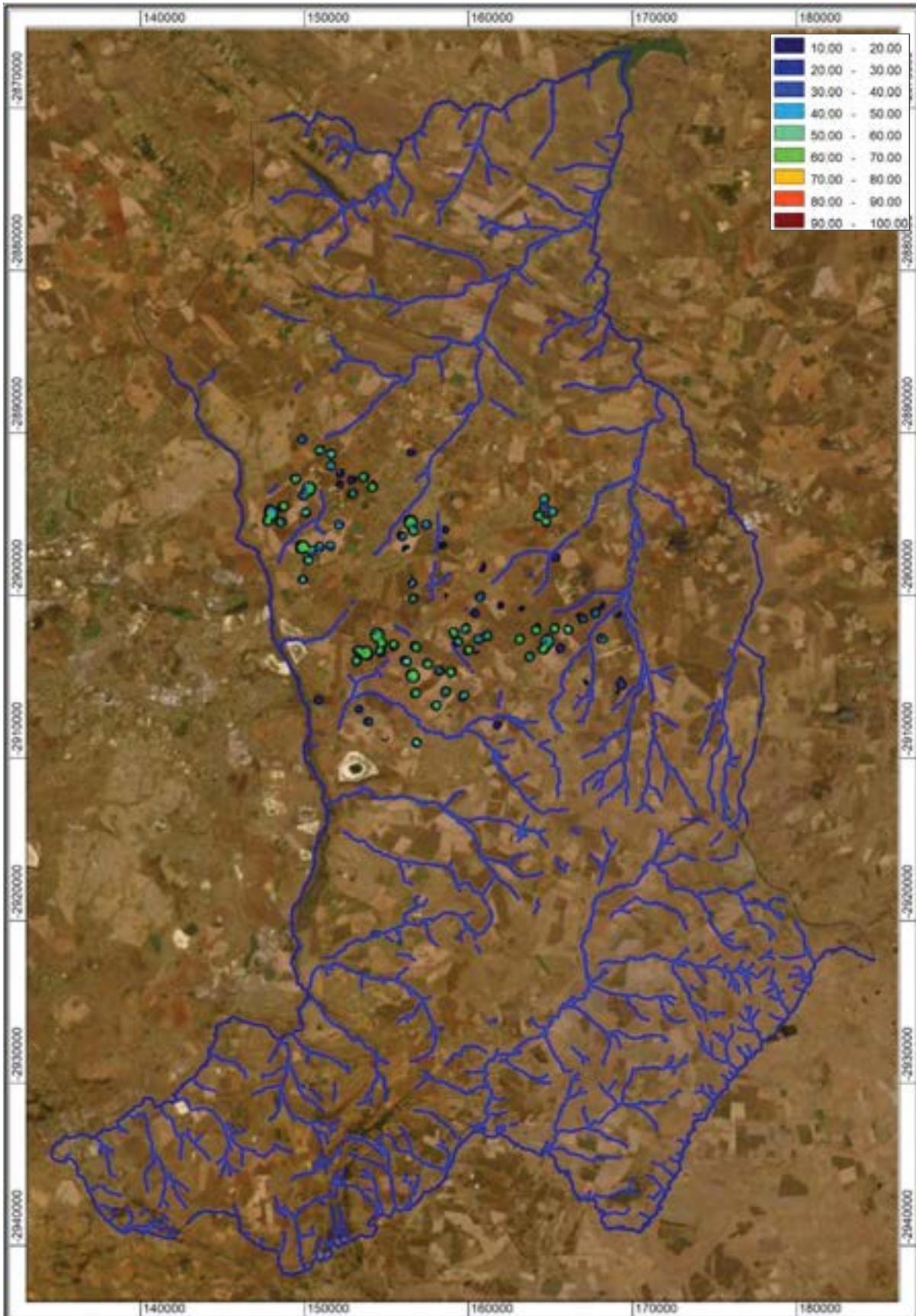
A3- Irrigation Return Flow Plumes after 25 years for the 2 400 ha Scenario with Dispersed Irrigation Pivots.



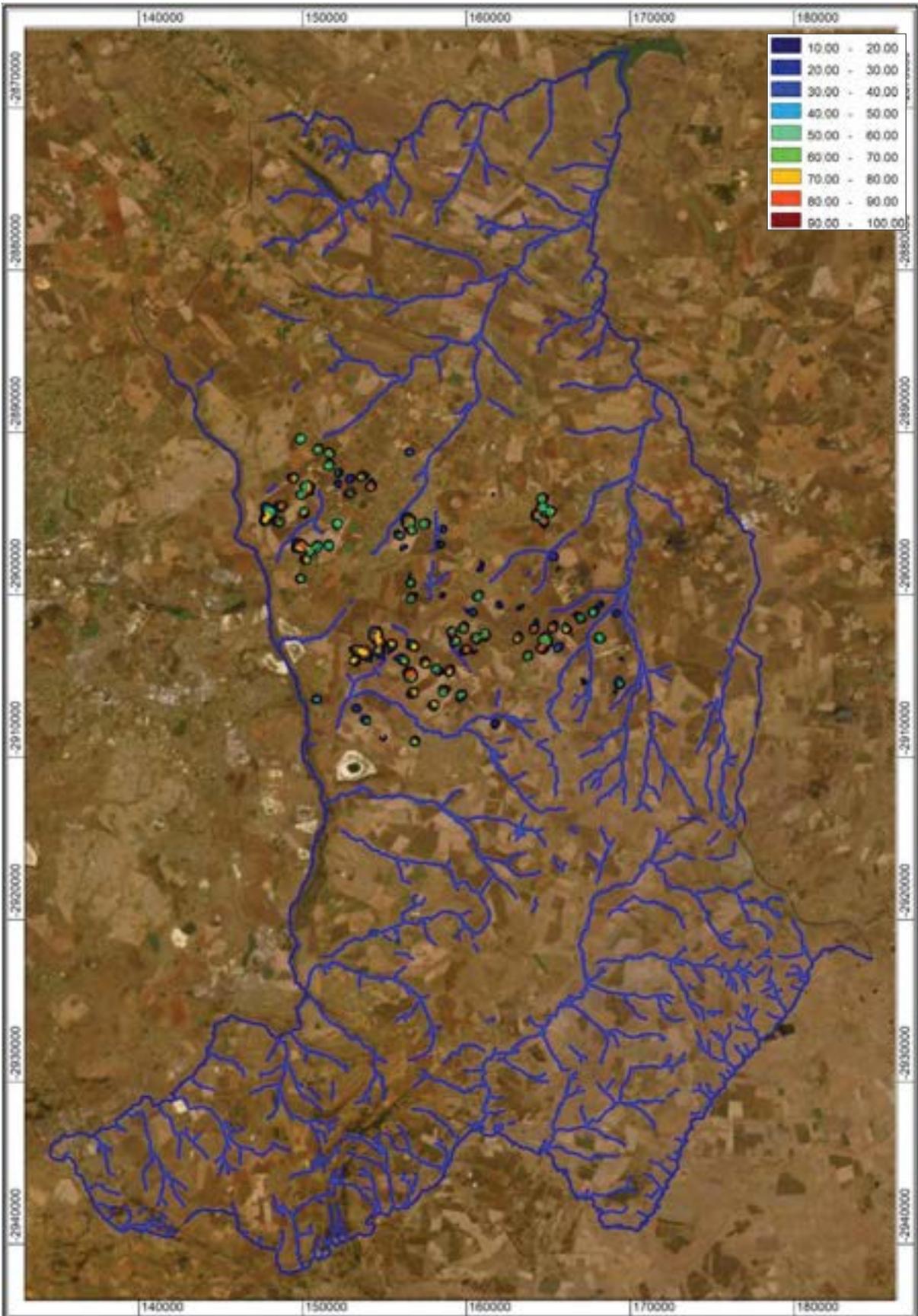
A4- Irrigation Return Flow Plumes after 50 years for the 2 400 ha Scenario with Dispersed Irrigation Pivots.



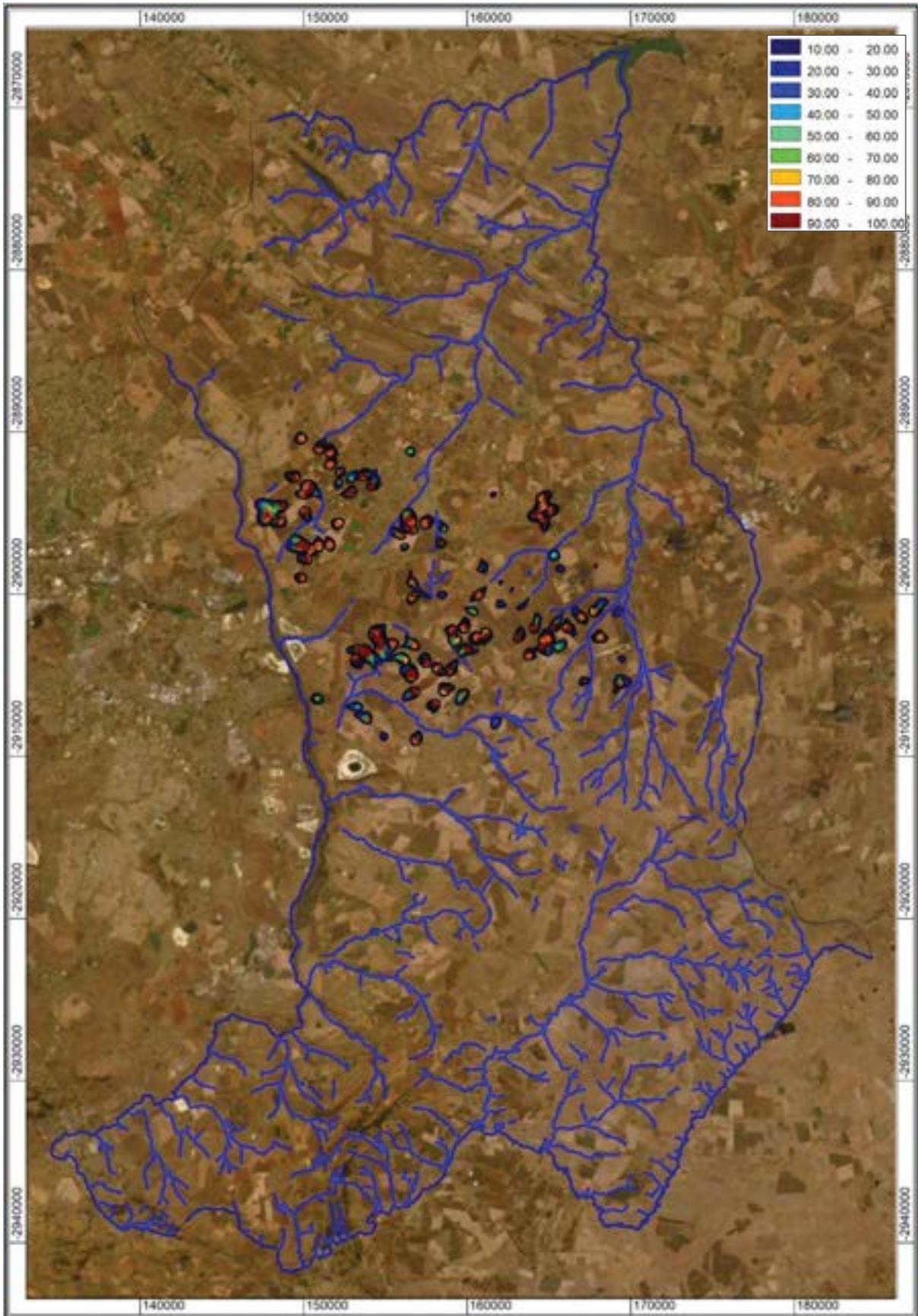
A5- Irrigation Return Flow Plumes after 5 years for the 2 400 ha Scenario with Concentrated Irrigation Pivots.



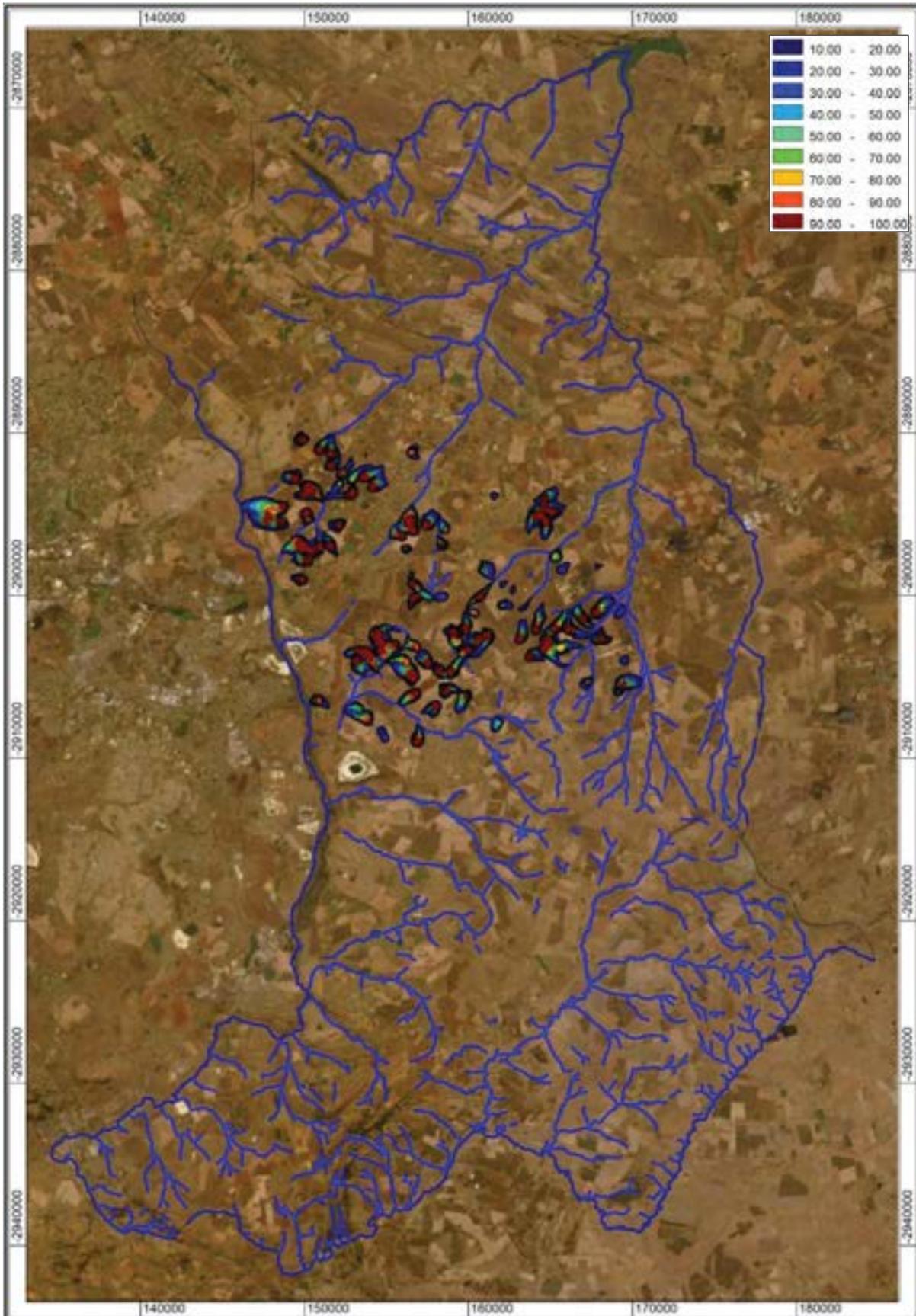
A6- Irrigation Return Flow Plumes after 10 years for the 2 400 ha Scenario with Concentrated Irrigation Pivots.



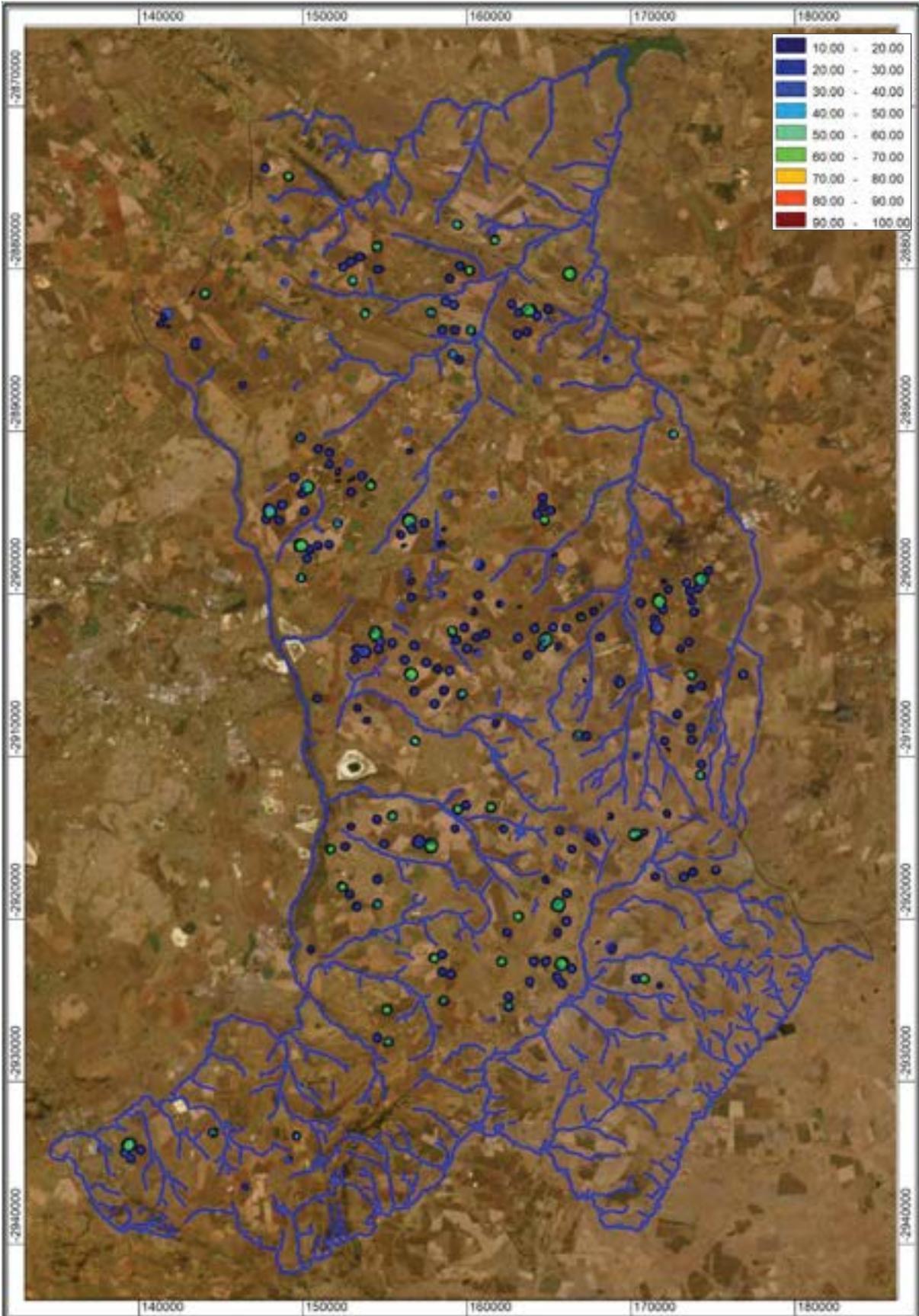
A7- Irrigation Return Flow Plumes after 25 years for the 2 400 ha Scenario with Concentrated Irrigation Pivots.



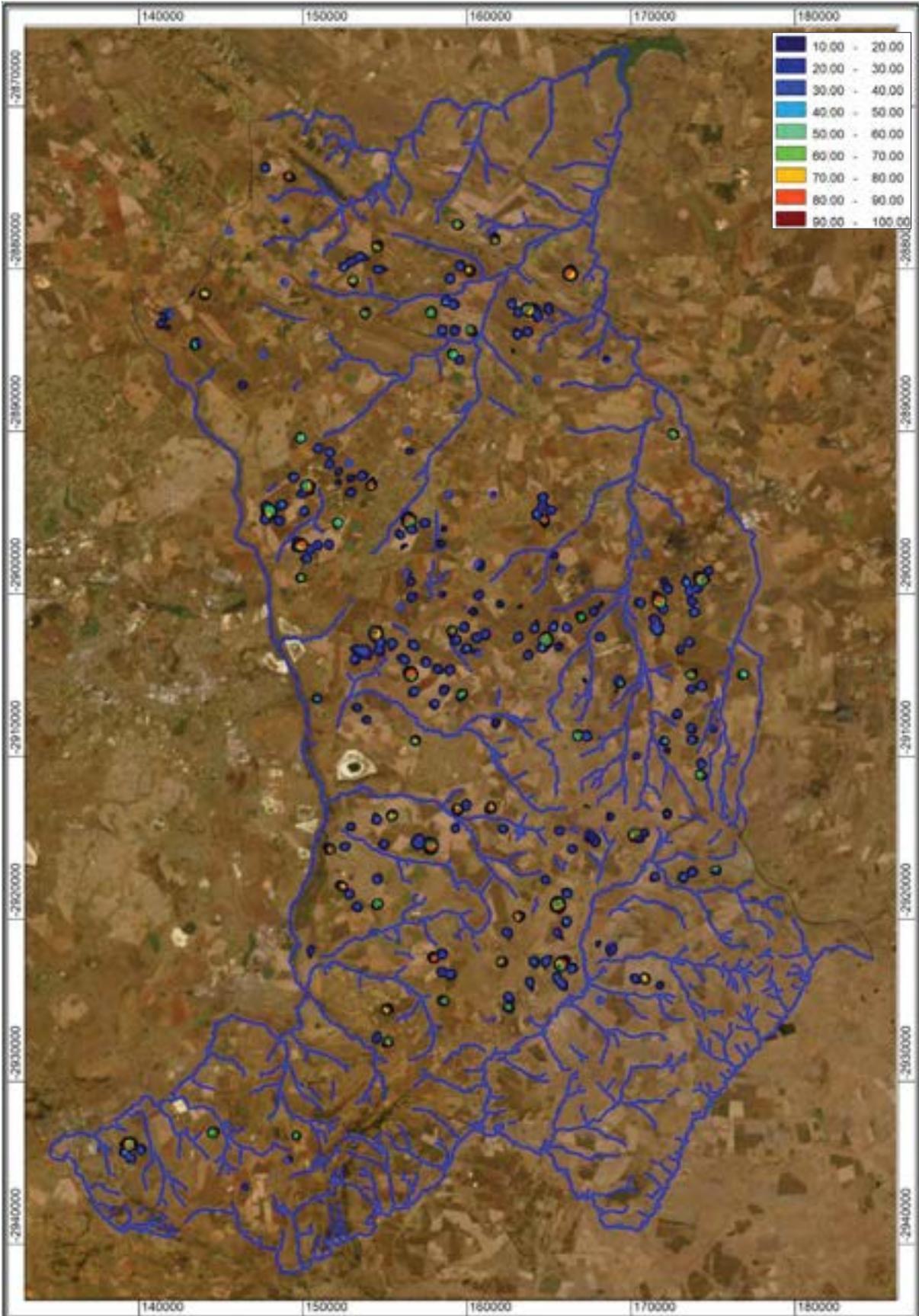
A8- Irrigation Return Flow Plumes after 50 years for the 2 400 ha Scenario with Concentrated Irrigation Pivots.



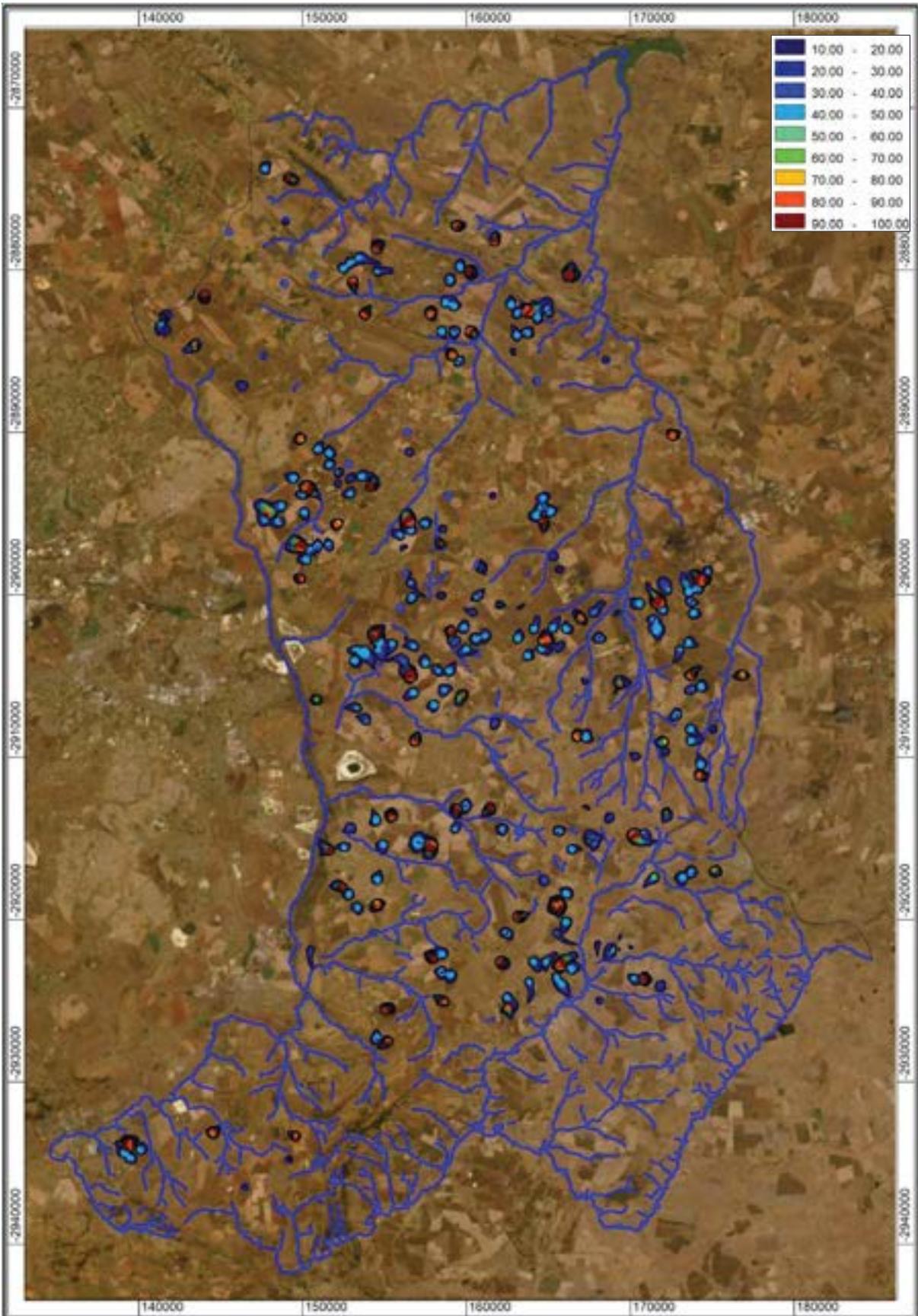
A9- Irrigation Return Flow Plumes after 5 years for the 6 000 ha Scenario with Dispersed Irrigation Pivots.



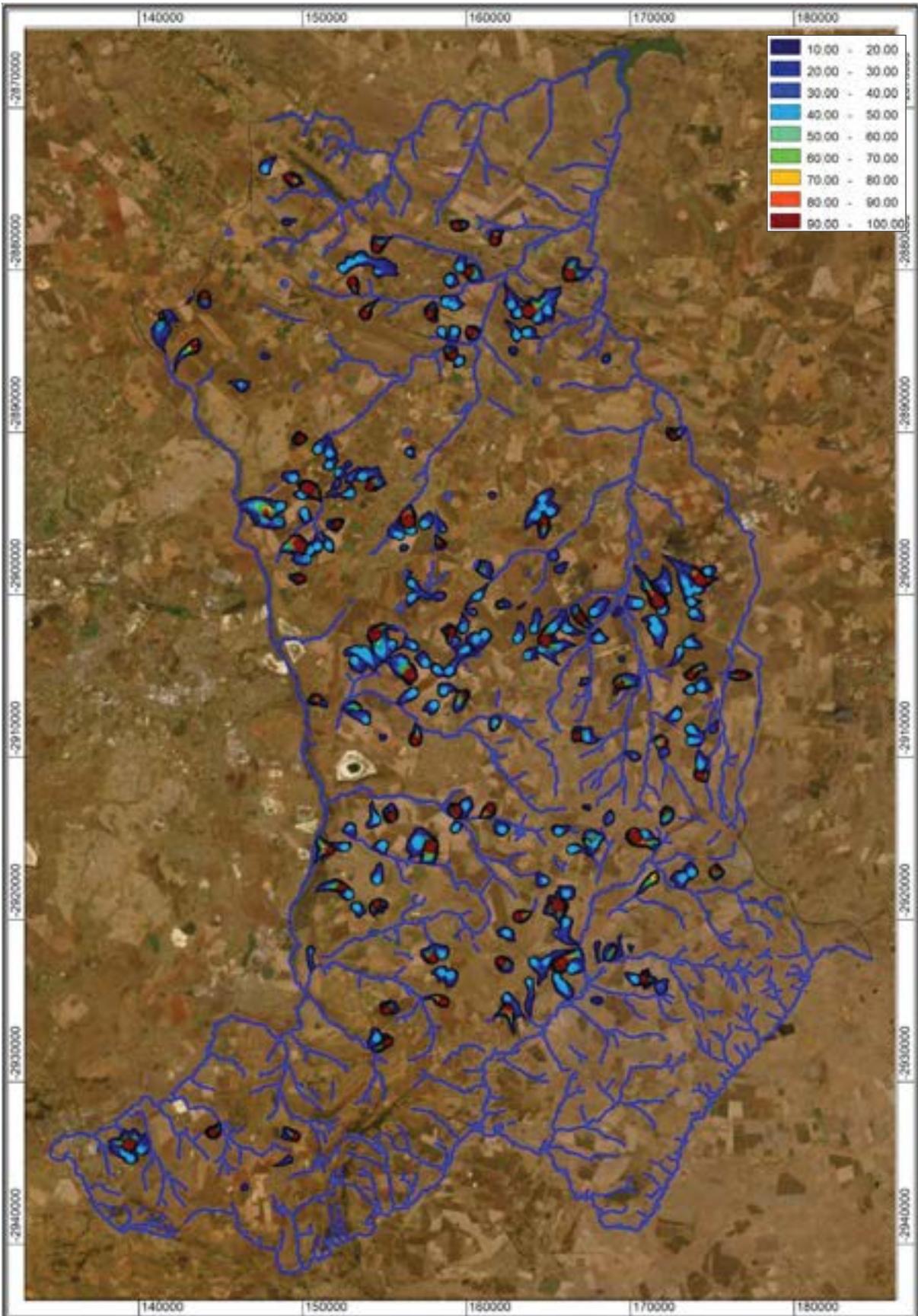
A10- Irrigation Return Flow Plumes after 10 years for the 6 000 ha Scenario with Dispersed Irrigation Pivots.



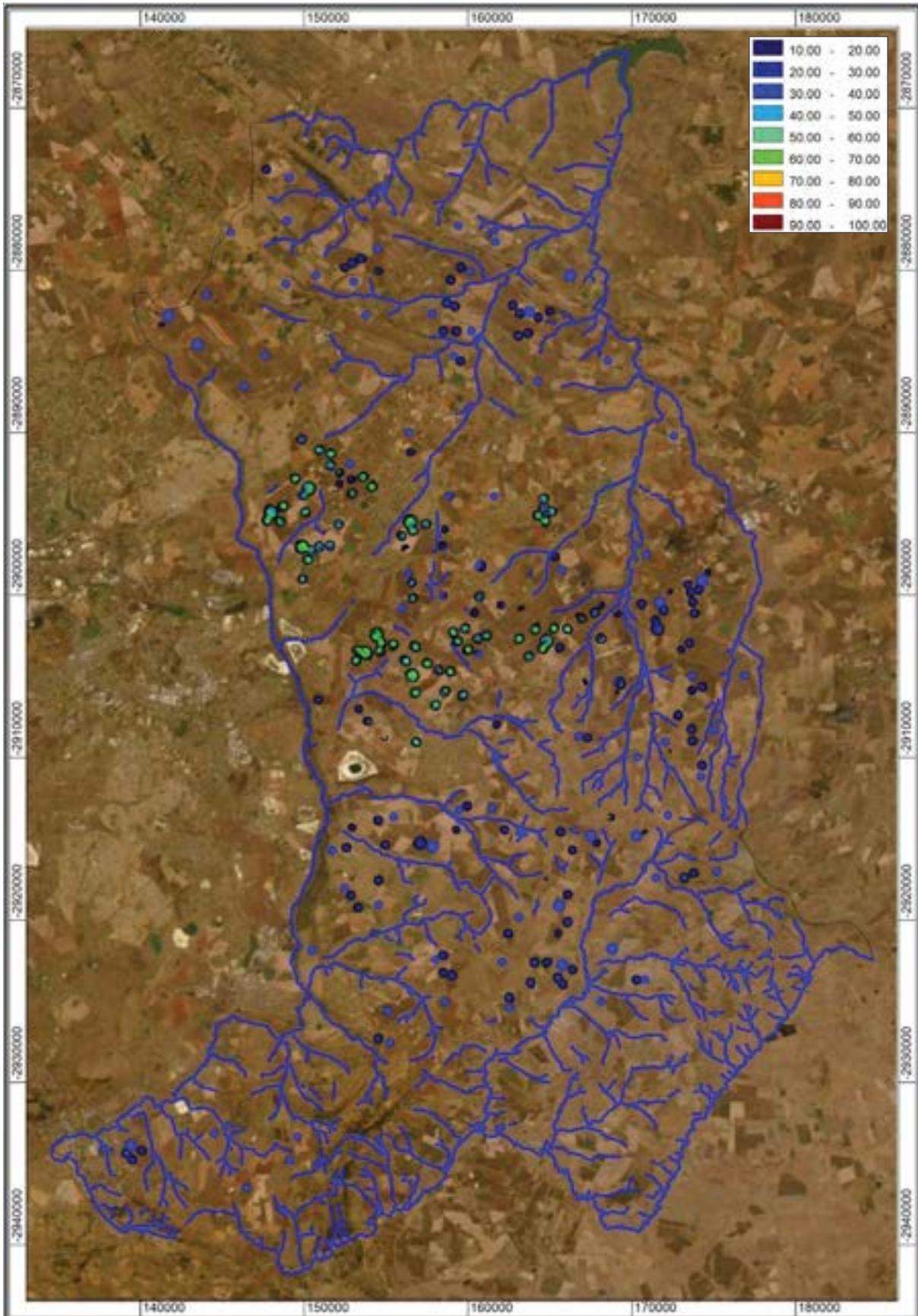
A11- Irrigation Return Flow Plumes after 25 years for the 6 000 ha Scenario with Dispersed Irrigation Pivots.



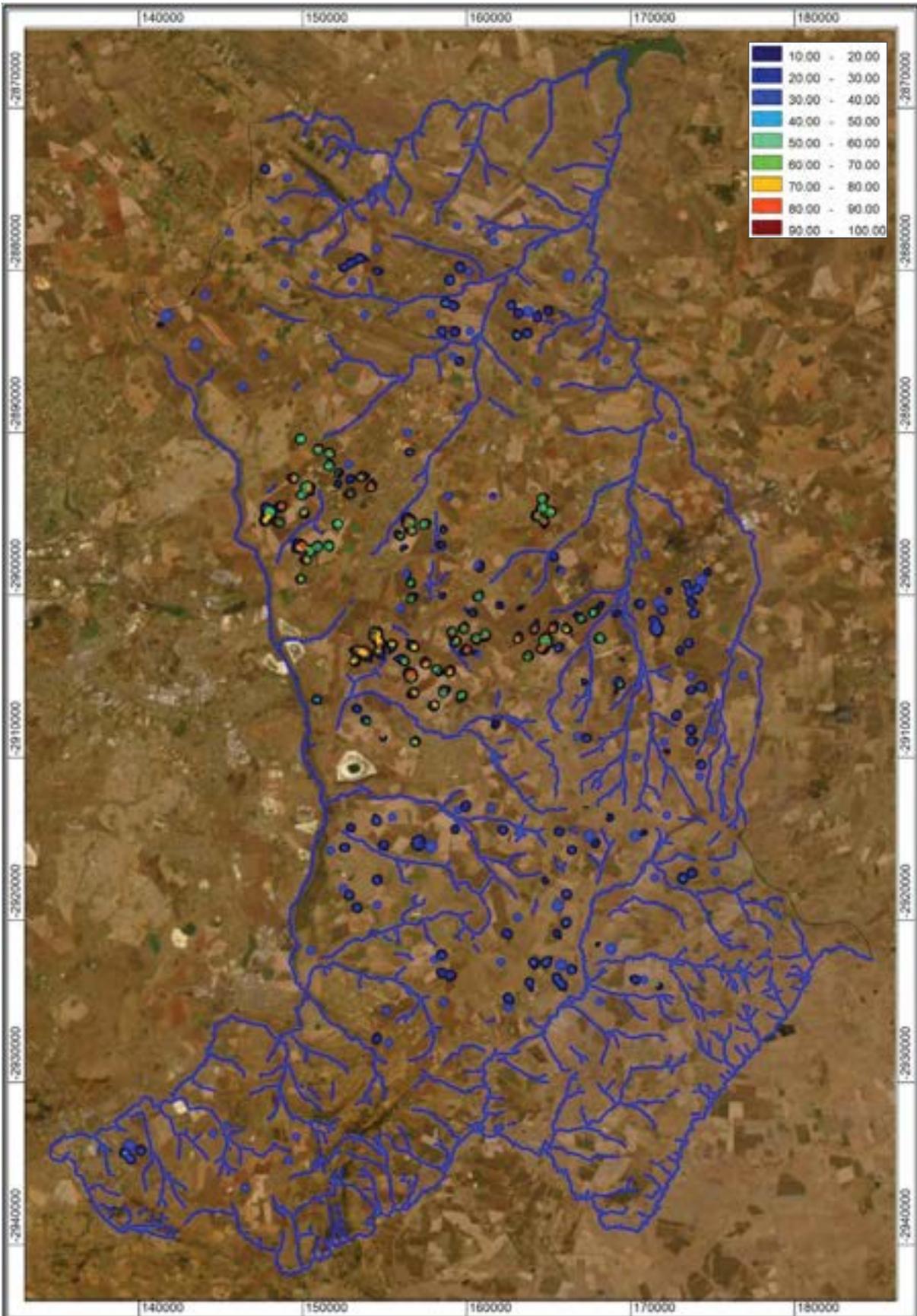
A12- Irrigation Return Flow Plumes after 50 years for the 6 000 ha Scenario with Dispersed Irrigation Pivots.



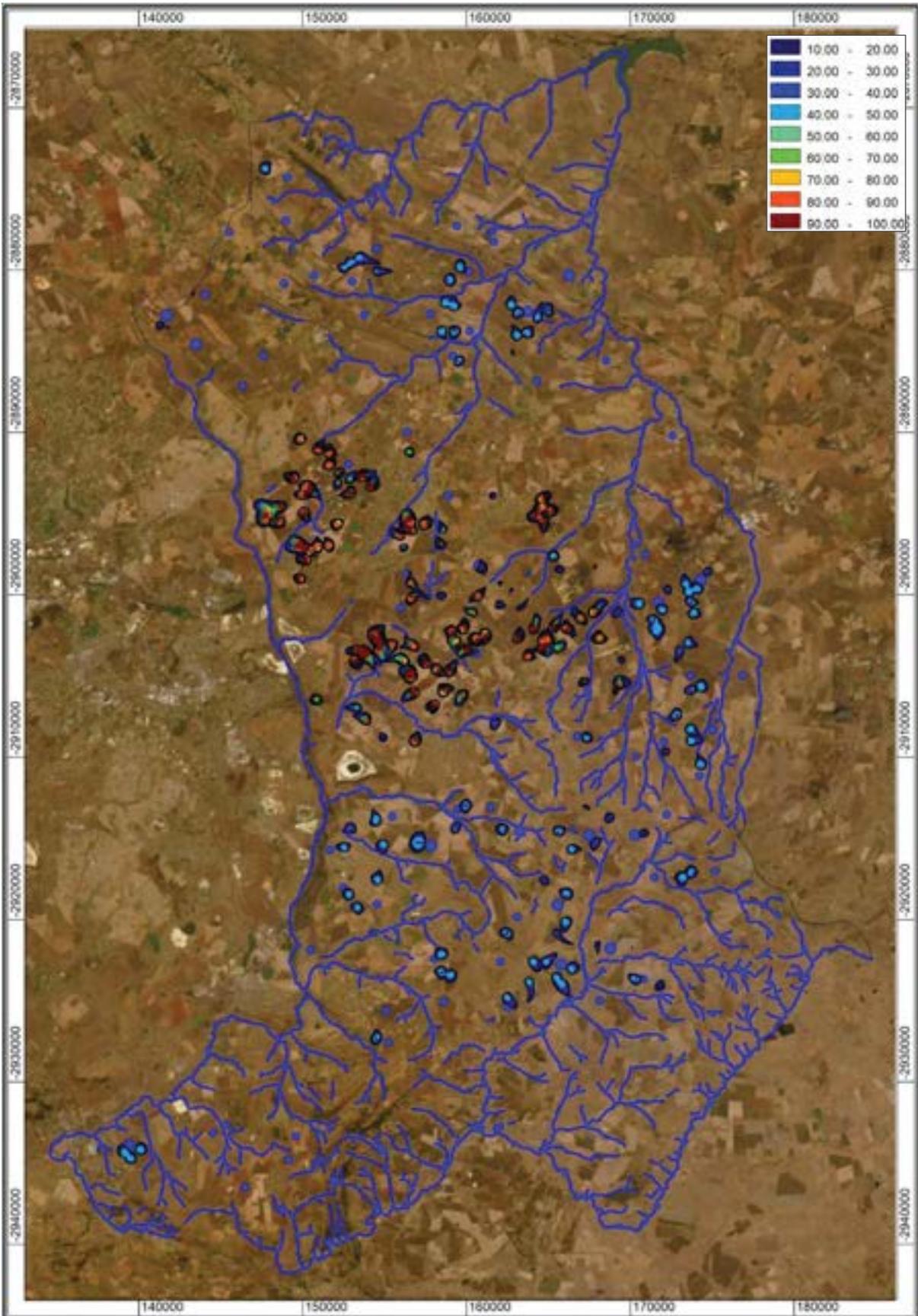
A13- Irrigation Return Flow Plumes after 5 years for the 6 000 ha Scenario with Concentrated Irrigation Pivots.



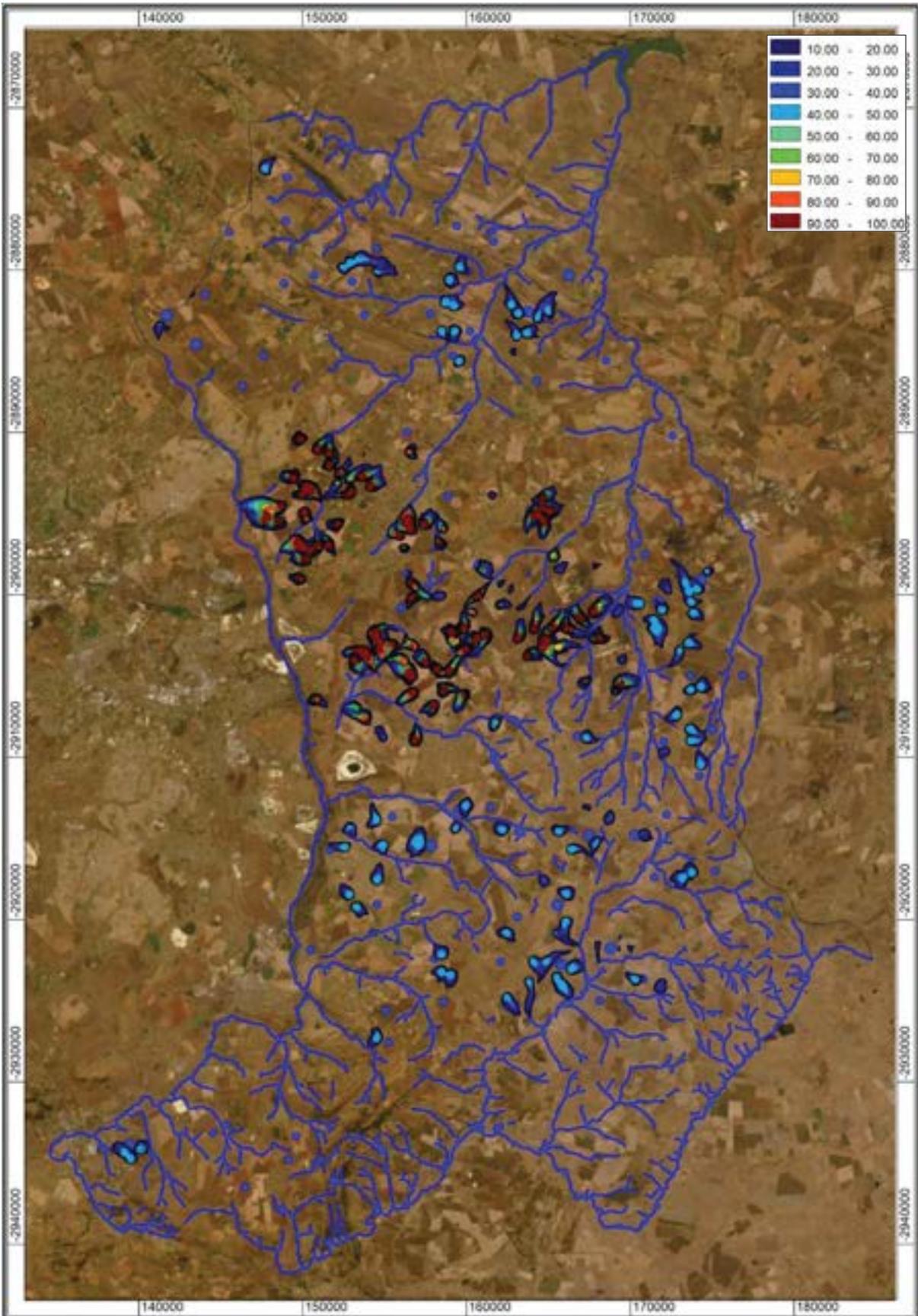
A14- Irrigation Return Flow Plumes after 10 years for the 6 000 ha Scenario with Concentrated Irrigation Pivots.



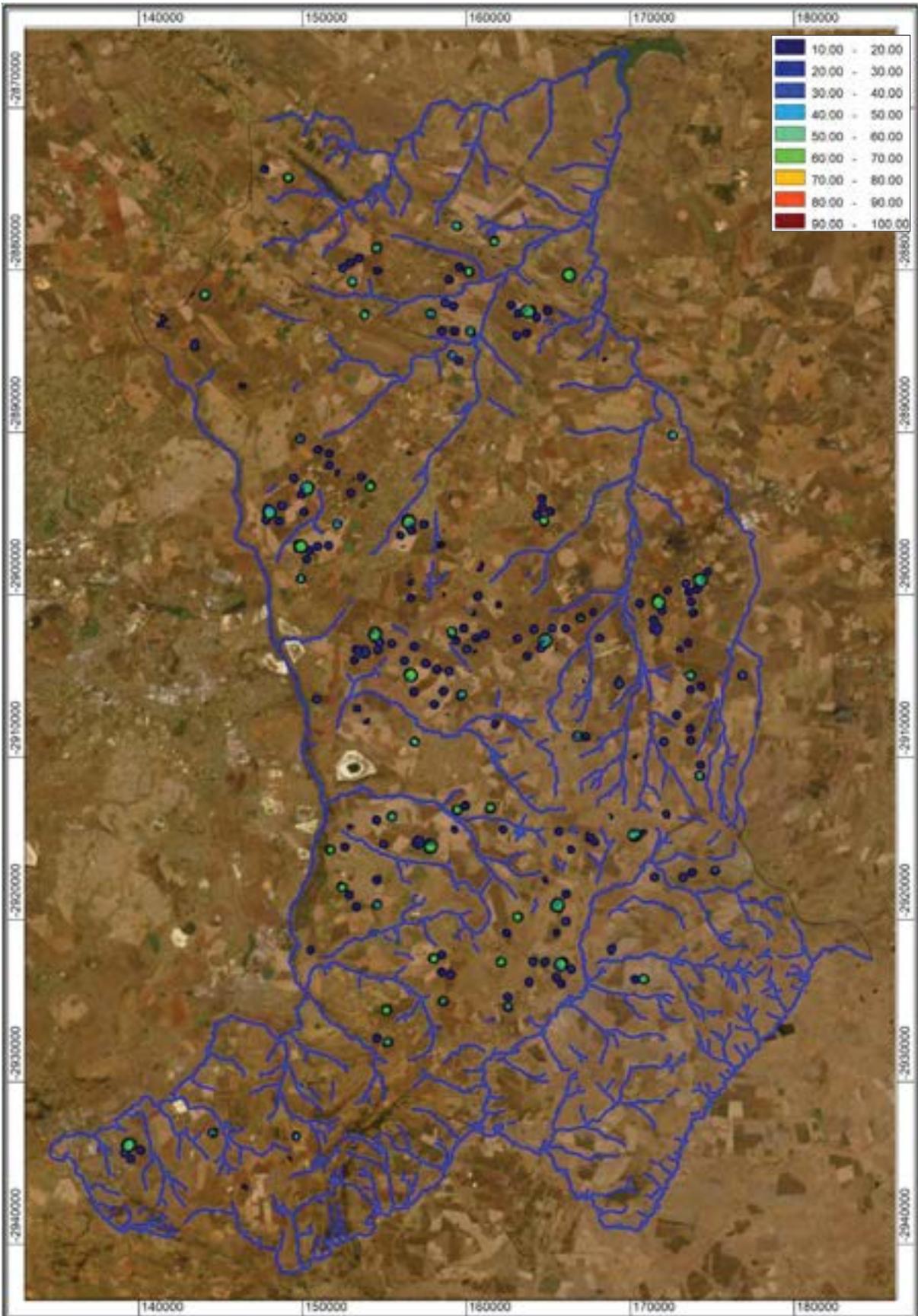
A15- Irrigation Return Flow Plumes after 25 years for the 6 000 ha Scenario with Concentrated Irrigation Pivots.



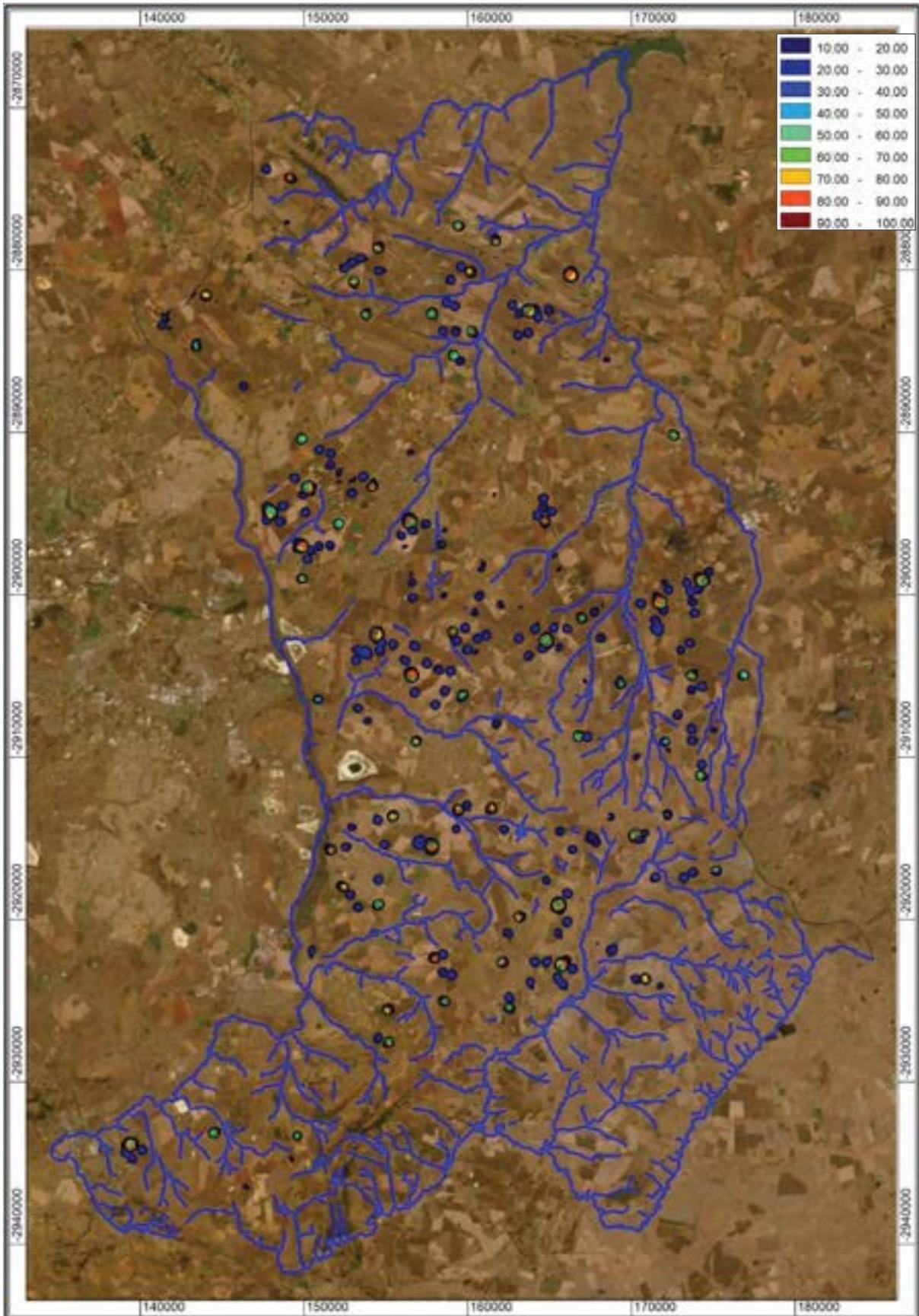
A16- Irrigation Return Flow Plumes after 50 years for the 6 000 ha Scenario with Concentrated Irrigation Pivots.



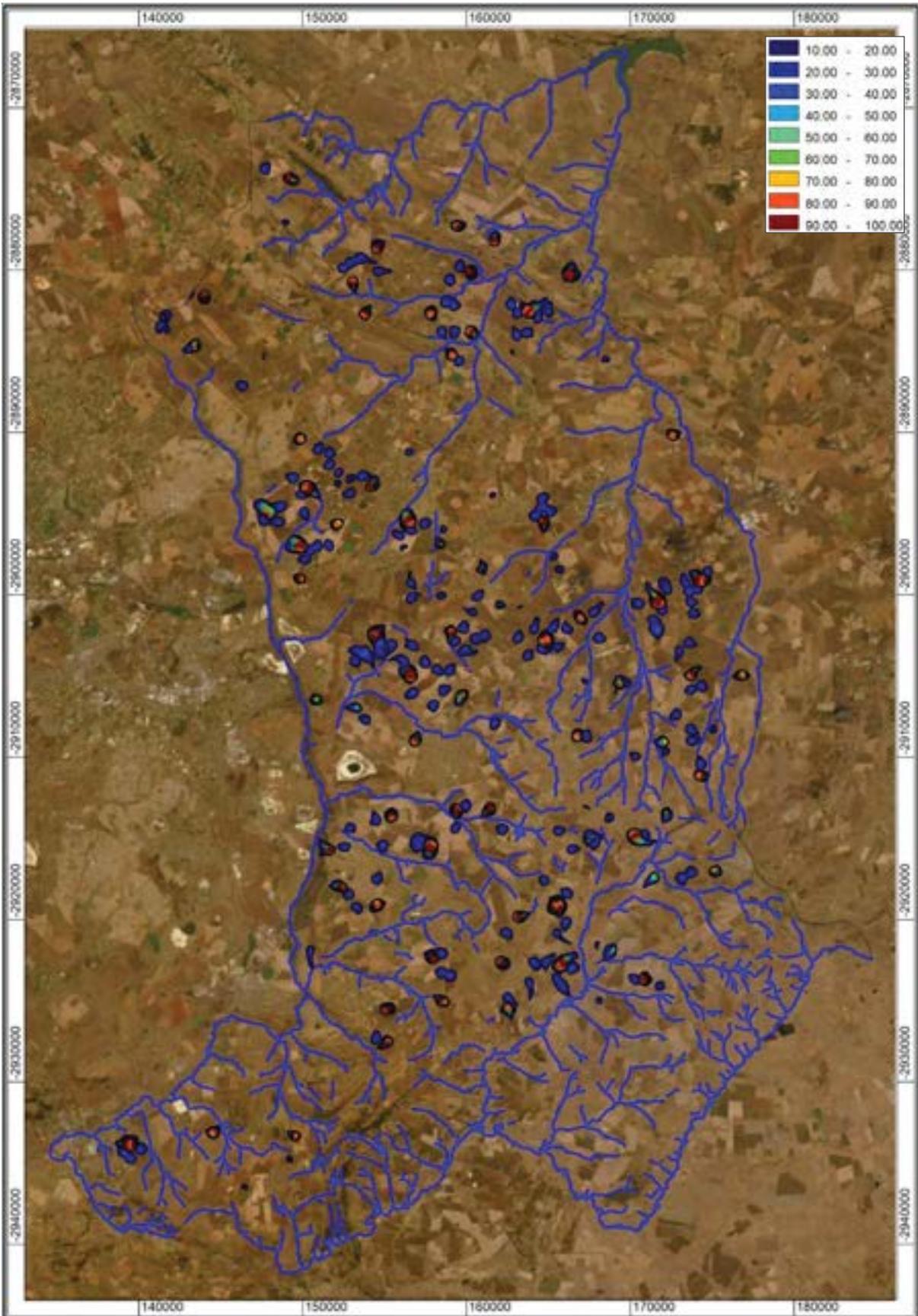
A17- Irrigation Return Flow Plumes after 5 years for the 6 000 ha 3:1 Scenario with Dispersed Irrigation Pivots.



A18- Irrigation Return Flow Plumes after 10 years for the 6 000 ha 3:1 Scenario with Dispersed Irrigation Pivots.



A19- Irrigation Return Flow Plumes after 25 years for the 6 000 ha 3:1 Scenario with Dispersed Irrigation Pivots.



A20- Irrigation Return Flow Plumes after 50 years for the 6 000 ha 3:1 Scenario with Dispersed Irrigation Pivots.

