Groundwater abstraction and woodland mortality: lessons from Namibia

E. Brunette[1,2]*, L. Wang[3] and T.D. Wassenaar[1,2]

1. Gobabeb – Namib Research Institute, Namib Ecological Restoration and Monitoring Unit, P.O. Box 953, 13013, Walvis Bay, Namibia.

2. Namibia University of Science and Technology, Private Bag 13388, Windhoek, Namibia

3. Department of Earth and Environmental Sciences, Indiana University Indianapolis, Indianapolis, IN 46202, USA.

*Corresponding Author

Email addresses: elbeb@gobabebtrc.org or beckerelbe@gmail.com (E. Brunette), lxwang@iupui.edu (L. Wang), twassenaar@nust.na (T. Wassenaar)

Abstract

In response to escalating worldwide groundwater dependence amid climate change, accurate estimation of sustainable groundwater yield becomes crucial. This study, conducted in Namibia, a semi-arid country heavily reliant on groundwater, investigated the impact of abstraction on tree mortality. We compared tree mortality around production boreholes with monitoring boreholes and we correlated groundwater decline rates with tree mortality, establishing a model from which we derived a groundwater decline rate range limit. Ana tree mortality was significantly higher (P = 0.01) around production boreholes (13.3%) than around the monitoring boreholes (0%). In dammed Swakop River, Ana tree mortality correlated with decline rates (r_S = 0.64, P < 0.01). The study suggests that decline rates of above 0.2 to 0.23 cm day^{-1} may cause elevated mortality (3-7%) and should not be sustained for extended periods. Rates exceeding 0.5 cm day^{-1} should be avoided, while monitoring is recommended for rates between 0.23 and 0.5 cm day^{-1}. Woodlands in rivers with altered flood

frequencies may be more sensitive to groundwater abstraction than previously thought. The study's methods offer a universal framework for refining sustainable yield calculations worldwide.

Keywords

Ecosystem sensitivity, mortality, phreatophyte, withdrawal, sustainable yield, woodland.

1 Introduction

Increasing pressure on scarce and dwindling water resources is a global phenomenon (Zektser & Everett 2004) that is particularly prevalent in the world's arid zones (Wang *et al*. 2022). The current situation in these regions foreshadows what may lie in store for most of the globe. The recent occurrence of widespread droughts, that are becoming more common in world regions where fresh water was once abundant (Perrone 2020), brought this issue into sharper focus.

Namibia, Africa's driest country south of the Sahara (Wanke *et al*. 2014) faces the double challenge that its economic growth depends on water-hungry sectors such as mining, agriculture and tourism within the broad context of a potentially drier and warmer future (Dirkx *et al*. 2008). This has already put severe pressure on Namibia's limited water resources (Dirkx *et al*. 2008; Remmert 2017). As in many water-scarce parts of the world, securing water for human use in Namibia tends to outweigh the environmental consequences of over-exploitation (Pahl-Wostl *et al*. 2013). This is despite the recognition that maintaining ecosystem integrity is not only a principle of sustainable development but also critical for the survival of people (Bethune, Amakali & Roberts 2005).

In the driest western parts of Namibia, the riparian ecosystems of all its western-flowing ephemeral rivers represent a key example of this conflict between human and environmental demands on water. Riparian trees access groundwater (Schachtschneider 2010; Schachtschneider and February 2013; Shadwell and February 2017), and in the absence of surface water, the riparian woodlands are a crucial component of this ecosystem that sustains riparian fauna. Indigenous communities have, over centuries, developed a highly structured and culturally regulated dependence on the riparian ecosystem (Jacobson *et al*. 1995). Despite their ephemeral nature, the rivers are important ecosystem service providers that must be managed sustainably.

In Namibia, human impacts on alluvial groundwater since the 1970s have taken two forms. First, the construction of major dams by the late 1970s reduced flood frequencies and volumes, and therefore also aquifer recharge, particularly in the Swakop River (MME 2010). The resulting reduction in flood frequencies was linked to reduced recruitment rates and increased mortality in Ana trees (Douglas *et al*. 2016; 2018). Second, beginning in the 1920s (Müller 2011) the water scheme to supply the coastal town of Walvis Bay was developed and abstraction of groundwater from the Kuiseb aquifer for human use significantly increased since the 1960s (Heyns *et al*. 1998). In the late 2000s, abstraction further increased due to the development of mines and subsequent growth of coastal towns (MME 2010). The ecological effects of human impacts on the hydrological regime of these ephemeral rivers could range from increased tree mortality tree to negative impacts on reproduction and result in the decline of riparian woodlands. Such effects have been documented in many ephemeral rivers and streams worldwide, including Australia (Doody *et al*. 2013; Kath *et al*. 2014) and the USA (Stromberg, Tiller & Richter, B. 1996). Although little research has been done on the resulting secondary impacts on human communities, there is evidence of cascading impacts on livelihoods (Dieckmann *et al*. 2013).

Three tree species (all Family *Fabaceae)*, Camel thorn tree *Vachellia erioloba* (E. Mey.) P.J.H. Hurter, Ana tree *Faidherbia albida* (Delile) A. Chev. and the non-native invasive Mesquite tree *Prosopis glandulosa* Torr. make up a major part of riparian woodlands of the central Namib (Dean, Milton & Jeltsch 1999). All three species were shown to switch from vadose to phreatic water depending on which is available (Schachtschneider 2010; Schachtschneider and February 2013; Shadwell and February 2017). During the flowing and non-flowing phase of the river, water is available in both the vadose and phreatic zones. In the dry-phase, however, water will only be available in the phreatic zone. If the abstraction rate exceeds the aquifer's recharge rate, the groundwater depth will increase.

If the groundwater depth increases beyond a certain threshold, depending on tree species' rooting depth and the availability of vadose water at the time, this could increase tree mortality. In a study conducted by Ward and Breen (1983), the sensitivity of Ana tree to water stress was demonstrated and widespread Ana tree mortality in the Kuiseb River was attributed to groundwater decline. In 2012, several mortality events of Ana tree in the Khan and Swakop rivers over the previous two decades were anecdotally attributed to over-abstraction. A preliminary study based on visual assessments by Mannheimer (2012) did not identify changes in groundwater depth in that aquifer section and concluded that the tree mortalities must have a different cause. However, it was acknowledged that further research was needed to verify this.

Groundwater depth is only part of the story. Riparian vegetation would have also adapted to the average rates of change in groundwater levels resulting from the balance between losses to evapotranspiration and decanting, and gains during recharge events (Jacobson *et al*. 1995; Heyns *et al*. 1998). However, groundwater abstraction and the interception of surface discharge for human use are expected to cause groundwater decline rates exceeding what riparian ecosystems would have experienced prior to human development. A vegetation monitoring project in the Khan River suggested that groundwater decline rates of as little as 10 cm per month (0.3 cm day^{-1}) may have led to the deterioration of Ana tree health, with more plants showing signs of canopy dieback (Müller 2003).

If abstraction has an abnormal impact on tree health and mortality, and thus on the structure and integrity of the riparian ecosystem it should be relatively straightforward to manage by setting sustainable groundwater yield limits, a practice that is well established in the field of geohydrology (Alley, Reilly & Franke 1999). However, to include the impact of abstraction on ecosystem health in this calculation, knowledge of the riparian vegetation rooting depth and vegetation's dependency on groundwater is necessary (Dennis, Van Tonder, Reimann 2002). These variables should ideally be determined through systematic investigation in each case, but such determinations are logistically challenging and expensive. As an expedient measure, it is often assumed that rooting depth and groundwater dependence are the same across species and ecosystems, or this aspect is entirely disregarded. Nevertheless, finding accurate methods to determine ecosystem sensitivity to abstraction is crucial. Doing so will facilitate the development of more effective strategies to mitigate development impacts on ecosystems reliant on groundwater and will define the risks that climate change may present to vital ecosystem services more clearly.

In this study, we compare tree mortality around abstracted boreholes with non-abstracted boreholes to determine if abstraction affects tree mortality. As these aquifers were already influenced by abstraction, our study addresses the question of vegetation dependence on groundwater by correlating tree mortality of three key tree species (Camel thorn, Ana tree and Mesquite trees) with changes in groundwater availability. We ask specifically whether mean groundwater depth and/or groundwater decline rates correlate with percentage tree mortality close to production boreholes and deduce from our results the likely critical groundwater depth or the range of groundwater decline rates on which sustainable abstraction yields should be based. The rivers studied here were managed differently in terms of size and number of reservoirs, and the intensity of abstraction. Thus, at the landscape scale, we investigate whether there are differences between the three rivers in terms of tree numbers and mortality, groundwater depth, and groundwater decline rates.

2 Materials and methods

2.1 Study area

The central Namib is a hyper-arid desert characterised, by sparse vegetation consisting of xerophytic succulents and shrubs (Mendelsohn *et al*. 2002). The ephemeral Khan, Swakop and Kuiseb rivers (Fig. 1) drain their catchments from the country's inland plateau and course through the central Namib Desert toward the Atlantic Ocean (Jacobson *et al*. 1995). From source to mouth, the rivers run through an area that receives an annual precipitation ranging from 400 mm/a in the central highlands, to less than 50 mm/a in the Namib Desert to the west (Mendelsohn *et al*. 2002). The riparian vegetation contrasts markedly with the sparse desert vegetation, supporting numerous trees and shrubs, which in turn support a relatively high diversity of fauna (Jacobson *et al*. 1995). Dams and reservoirs in the upper reaches of the Swakop and Kuiseb store some of the periodic surface flows for water provision to towns and other human developments (Dirkx *et al*. 2008).

The hydrological model (BIWAC 2010) for these rivers suggests that the aquifers are subdivided into several compartments. Groundwater recharge of these compartments mainly occurs from surface flows at irregular and unpredictable intervals resulting from rainfall within the river catchment. Negligible throughflow occurs between compartments (BIWAC 2010), and under natural conditions, losses to compartments occur mostly through evapotranspiration. In the absence of abstraction, the groundwater decline rate for each compartment is therefore assumed to be a function of compartment dimensions and atmospheric vapour pressure deficit (VPD) that affect evapotranspiration rates. Transpiration rates are also reliant on vegetation density and the species of phreatophyte plants present, as this determines how they regulate their stomata in response to VPD. The finer-scale geomorphology and the water quality of the compartments were unknown and were assumed to be the same between compartments and rivers.

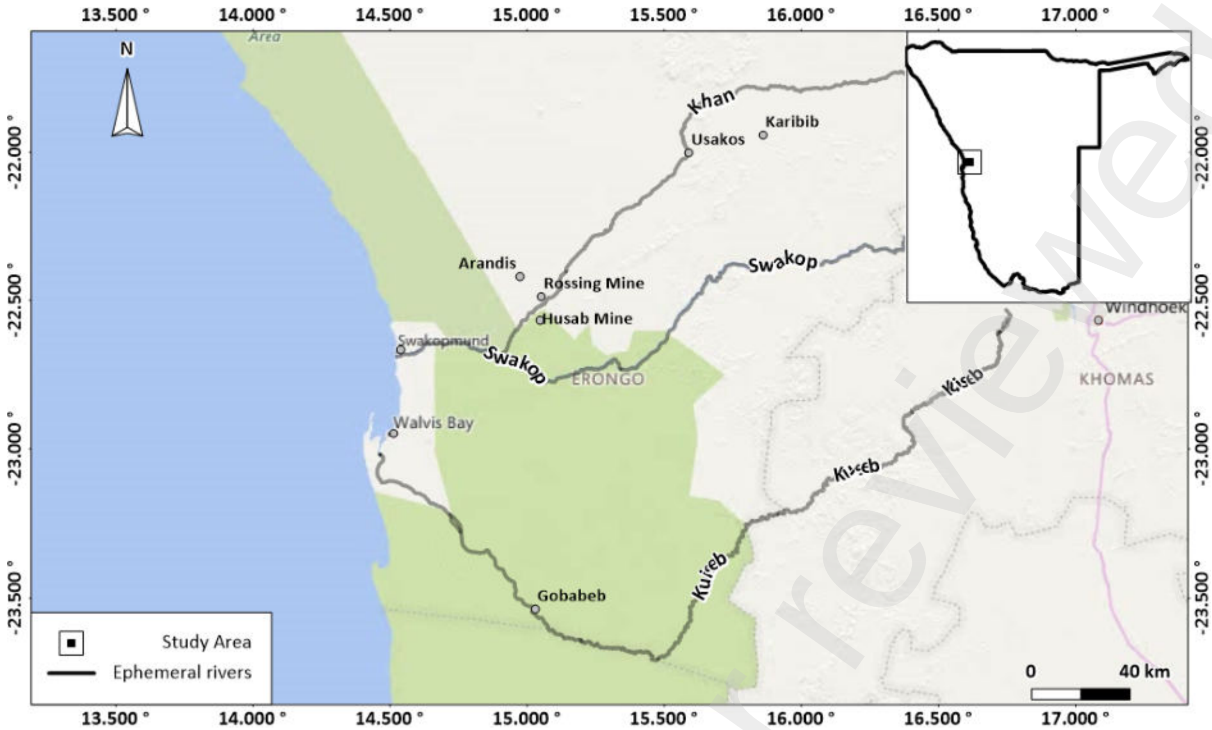


Figure 1. The ephemeral Kahn, Swakop, and Kuiseb rivers that were surveyed for numbers of dead and live trees in November/December 2016.

2.2 Data collection and analysis

2.2.1 Determining groundwater levels.

Borehole level data from 1994 to 2015 were acquired from Namwater, Langer-Heinrich-, Swakop Uranium- and Rössing Uranium mines. Personnel from these institutions measured the monthly groundwater depth in meters below the ground level (m b.g.l.) by inserting a water level dipper down the borehole. When the water level dipper attached to a measuring tape/band touches the water, it triggers an alarm or illuminates a bulb, allowing the water depth to be read from the measuring tape.

Due to the transmissivity of the alluvial medium, abstraction can impact the groundwater level and decline rates of an entire groundwater compartment (Van Vuuren 2012). Among the 19 boreholes in our data set, several occurred within the same compartment (Fig. 2), indicating that their hydrological dynamics were interconnected. Thus, the degree of hydraulic influence of production boreholes on nearby boreholes was considered in each case. Boreholes falling within the potential zone of influence of a production borehole, were labelled as production boreholes, while those that were outside the influence of production boreholes were termed monitoring boreholes. In the latter scenario, we assumed that groundwater decline rates resulted solely from evapotranspiration and decanting. The mean groundwater level was determined from the monthly groundwater depth data collected between 2009 and 2016.

Groundwater decline rates were calculated using monthly groundwater levels recorded between 1994 and September 2015. The slope of the best-fit line for groundwater levels measured between each recharge event was used to calculate the ground water decline rate for a borehole in that period. Thus, depending on the number of recharge events and the age of the borehole, some boreholes had more decline rates than others. We randomly selected four decline rates per borehole and calculated the average for each. Starting from 2006, regular groundwater monitoring in the Kuiseb River was discontinued, limiting the accurate determination of decline rates to two boreholes. As a result, Kuiseb River data was excluded from the groundwater depth comparison between the rivers (however, these values are presented in Fig. 3 for reference). We also evaluated if there were any difference in the average decline rates for production versus monitoring boreholes. When comparing means or medians between two groups, significance testing was conducted using either a student's T-test or a Wilcoxon rank sum test, depending on whether the conditions for normality were met.

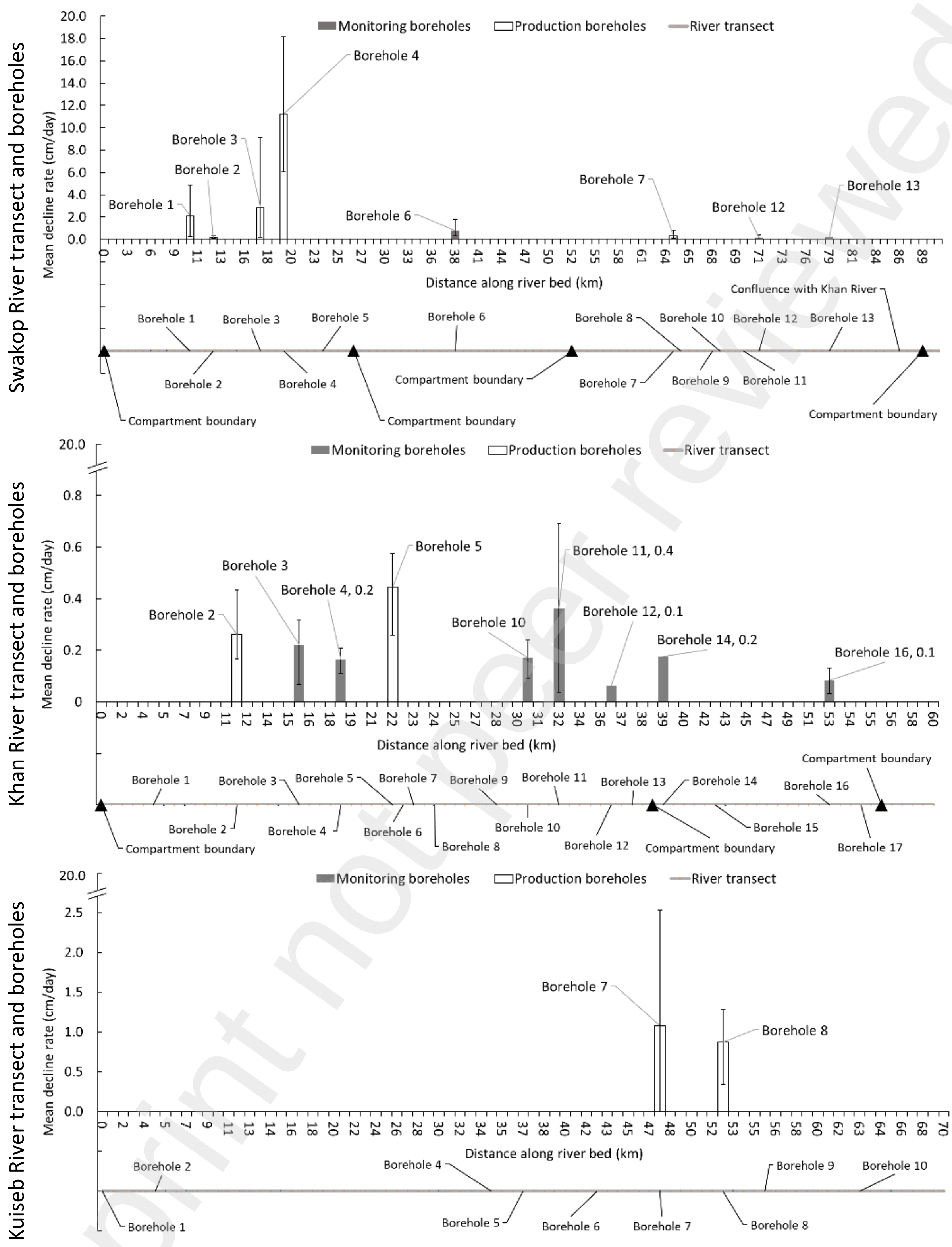


Figure 2. The mean groundwater decline rates of the 19 boreholes and their relative position along the Swakop, Khan and Kuiseb rivers around which tree mortalities were observed. Beneath the bar graphs, a schematic of the river transect is depicted, including the borehole positions and compartment boundaries (marked with black triangles). Error bars indicate maximum and minimum values. Bars without maximum and minimum values had only one measurement. Note the different scales on the Y-axis between the three graphs.

2.2.2 Tree census data collection

Tree census data were collected in November 2016 through transect surveys in the Swakop, Khan and Kuiseb rivers. A relevant research permit was obtained from the Ministry of Environment, Forestry and Tourism: authorisation number AN20200213. Four observers drove in a four-wheel drive vehicle along the midline in each of the rivers for a total transect length of 55 km in the Khan River, 88 km in the Swakop River and 91 km in the Kuiseb River. The distances varied because of obstacles in the river that presented accessibility challenges, but the start and end of the transects in each river were approximately the same distance from the coast and hence all fell roughly into the same precipitation band. This consistency was crucial because, although floods originating from upper catchment areas primarily supply water to the woodlands, anecdotal observations made by us, and later corroborated by Douglas *et al*. (2018), indicated that local rainfall influenced tree density. Each observer counted the total number of dead and live trees observed in successive 200 m sections within the river channel. GPS coordinates were recorded using a handheld GPS device. The percentage of dead trees per 200 m section was calculated from this data. The tree survey was conducted near the expected end of an unusually long dry phase in November 2016. Without any flooding or local precipitation to recharge the alluvial aquifers for 18 months, the plants with deep taproots were assumed to be dependent on groundwater. It was during this phase that deep-rooted plants were expected to be vulnerable to groundwater abstraction.

2.3 Data analysis

2.3.1 Relating tree densities and mortality patterns to groundwater availability.

To relate tree density and the percentage dead trees in an area to ground water depth and decline rates, the geographic position of each 200 m section was charted on a map Quantum GIS Version 2.18 (QGIS Development Team 2017). The position of each borehole (n = 19) was plotted as a layer over the tree count data. A 2 km radius zone of influence was created around each borehole using the buffer function in QGIS. The polygons that were created intersected the longitudinal transects, creating 4 km-long river sections. All trees counted within the clipped 4 km sections were used to ascertain tree density in proximity to the nearest focal borehole. Tree density was calculated as the number of trees per kilometre (total number of trees divided by the transect length). Mortality was calculated as the percentage dead trees within each section. Tree densities and mortality were correlated with the ground water depth and groundwater decline rate (cm day^{-1}). Pearson's correlation was applied when all underlying assumptions were met; otherwise, a Spearman's correlation was used.

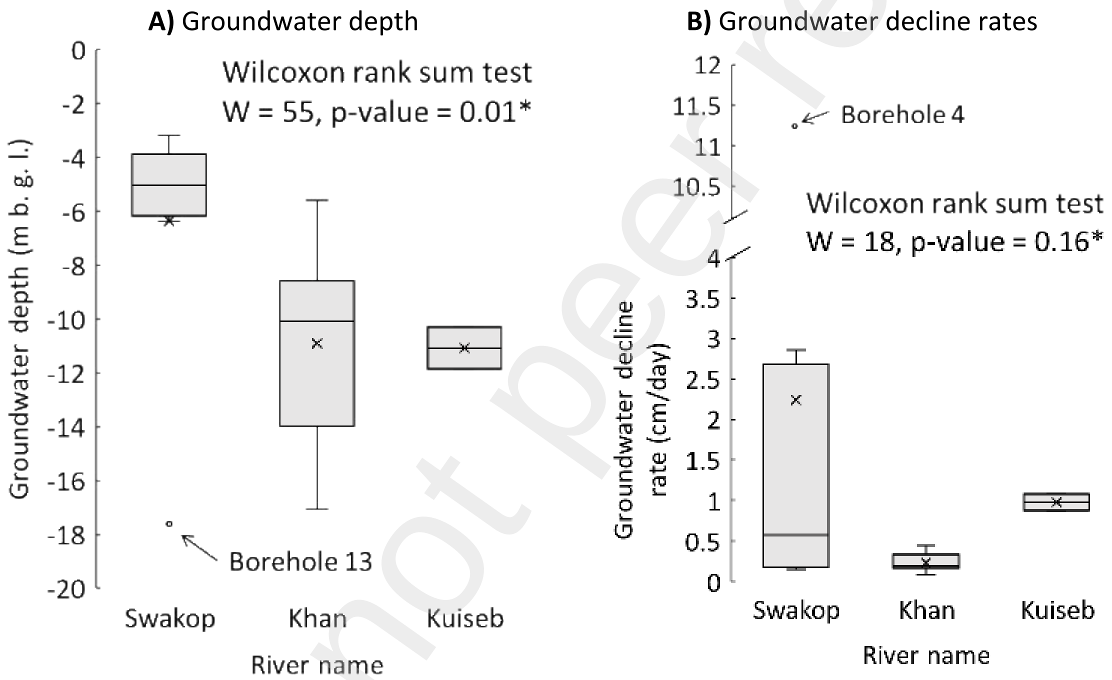
2.3.2 Predicting tree mortality based on groundwater availability.

If the correlated data indicated a potential relationship between tree mortality and groundwater depth/decline rates, the data were fit to various linear models using *R* (R Core Team 2018). It is important to note that while we do not intend to imply causality, the purpose of the model is to deduce critical values of abstraction applicable in management scenarios. Normality of the residuals were determined using the Shapiro-Wilk test. If all the assumptions for a linear model were met, a P-value was calculated to determine significance. In instances where assumptions for homoscedasticity and normality were not met, the data was either log-transformed or non-parametric tests were employed for significance testing. Residual plots and data visualization were generated using Excel (Microsoft, 2017).

3 Results

3.1 Groundwater depth and decline rates in the Kuiseb, Swakop and Khan rivers.

During the period spanning from 2009 to 2015, the Swakop River had the shallowest mean groundwater level, followed by the Khan and Kuiseb rivers (Fig. 3A). The only groundwater data that was available from the Kuiseb was from two production boreholes that had an average decline rate of 1.1 cm day^{-1}. Although the Swakop median decline rates were lower than the Kuiseb River median (Fig. 3B), the Swakop River mean was affected by three boreholes in the Langer Heinrich compartment that had exceptionally high decline rates (Fig. 2). Two of these were Swakop River monitoring boreholes (numbers 1 and 3) that were within the same compartment as the production borehole that had a groundwater decline rate of 11.2 cm day^{-1} (Fig. 2) and were thus sorted into the production group. The median decay rate for monitoring boreholes were 0.2 cm day^{-1} (with a maximum of 0.4 cm day^{-1}), while the mean decay rate at production boreholes was much higher ($P < 0.01$) at 2.2 cm day^{-1} (with a maximum of 11.2 cm day^{-1}) (Fig. 4).



*The Kuiseb River data, with only 2 data points, were excluded in this test.

Figure 3. Box-and-whisker plots illustrating A) the difference in groundwater levels in the Khan (8 boreholes), Swakop (9 boreholes) and Kuiseb (2 boreholes) rivers between 1994 and 2015, and B) the difference in groundwater decline rates at boreholes in the Swakop (8 boreholes), Kuiseb (2 boreholes) and Khan (9 boreholes) rivers from four randomly selected decay rates calculated from monthly groundwater levels that were recorded between 1994 and September 2015. The Swakop River has the shallowest groundwater levels, but the greatest variation in groundwater decline rates, with groundwater decline rates up to 50 times higher (11.2 cm day^{-1}) than rates observed in the Khan River (0.2 cm day^{-1}). With data for only two production boreholes, the Kuiseb River data was not included in the analysis, but the values are shown here for reference.

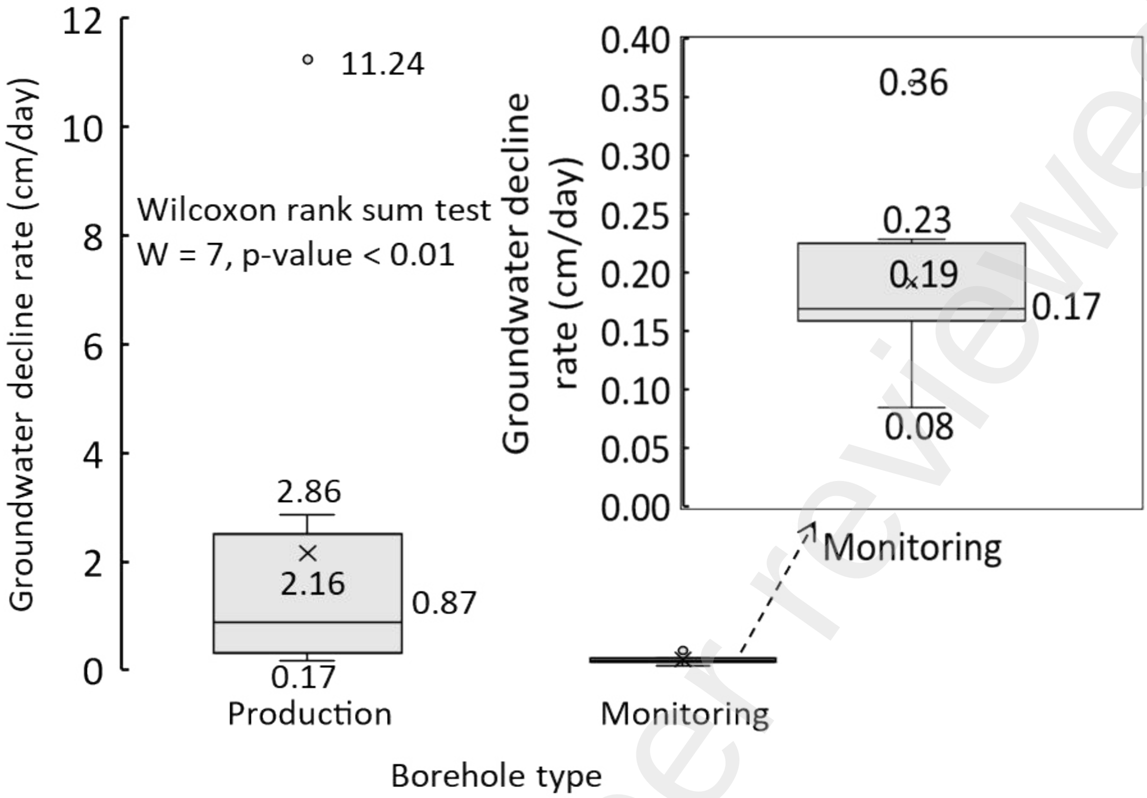


Figure 4. The groundwater decline rates at production versus monitoring boreholes. The average decline rate for each borehole was determined from four randomly selected decline rates that were calculated from monthly groundwater levels. These groundwater levels were recorded between 1994 and September 2015. Note the different scales used on the y-axis for production and monitoring boreholes. Groundwater decline rates were significantly higher (W = 7, P < 0.01) at production boreholes (2.2 cm day^{-1}), compared with monitoring boreholes (0.2 cm day^{-1}).

3.2 Tree census of the Kuiseb, Swakop and Khan rivers and how tree density is related to groundwater depth.

The surveyed section of the Kuiseb River had the most trees per kilometre at 223 trees/km, which was three times more than in the Swakop (66 trees/km) and almost six times more than in the Khan River (39 trees/km) (Fig. 5). In keeping with the findings by Visser (1998 cited by Strohbach *et al*. 2015), Mesquite trees were the dominant species in the study section of the Swakop River. Mesquite trees appear to be associated with shallow groundwater ($r(14) = -0.58$, $P = 0.02$) (Fig. 6). There was no correlation between groundwater depth and Camel thorn and Ana tree density.

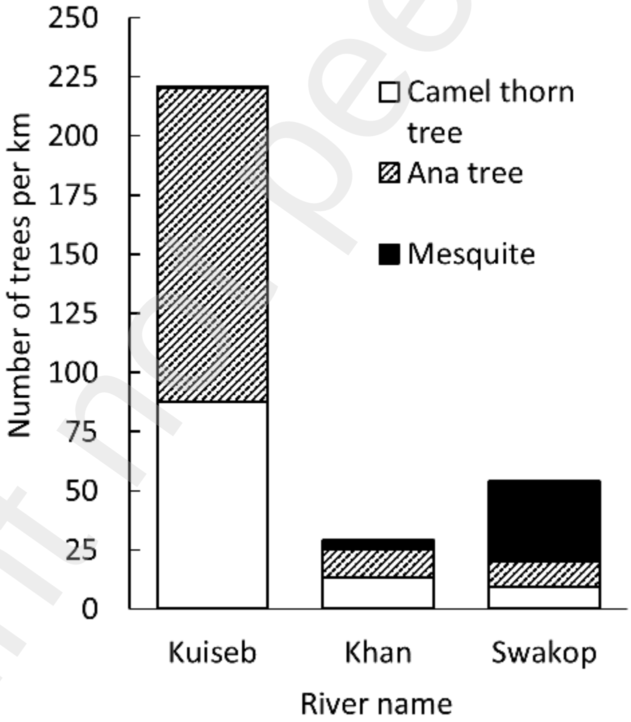


Figure 5. A comparison between the Kuiseb, Swakop and Khan rivers and the number of trees per kilometre. The stacked bar graph shows the proportion of this total that is made up of Camel thorn, Ana and Mesquite trees.

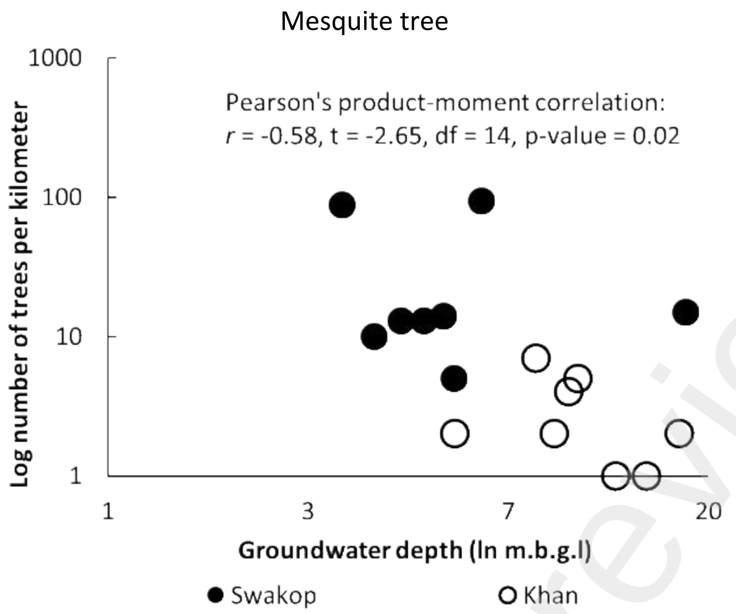


Figure 6. A correlation between the total number of Mesquite trees (dead plus alive) within 4 km sections of river (2 km upstream and downstream from a borehole) and the mean groundwater depth between 1994 and 2015. There were too few Mesquite trees in the Kuiseb river to include in this graph. Mesquite tree density correlates with groundwater depth, and lower tree densities associated with deeper groundwater.

3.3 Tree mortality, groundwater availability and the effect of abstraction

The Swakop River had a higher proportion of dead trees for all three species (between 13 and 21%) than the other two rivers (Fig. 7) despite having the shallowest mean groundwater level (Fig. 3). Tree mortality did not correlate with groundwater depth.

Tree mortality was significantly higher for Ana ($P < 0.01$) and Mesquite ($P = 0.05$) trees around production boreholes (Ana = 13.3% and Mesquite = 10%) than around monitoring boreholes (Ana = 1% and Mesquite = 2%) (Fig. 8). Tree mortality was similar between production boreholes and monitoring boreholes for Camel thorn ($P > 0.05$).

Evaluating all the decline rates that were measured at monitoring and production boreholes across all rivers (Fig. 9), only Ana tree mortality was associated with groundwater decline rates (rho = 0.64, S = 291.7, $P < 0.01$) (Fig. 9), with most of this pattern apparently driven by Ana tree mortality in the

Swakop River (r_S = 0.86, P = 0.01). This pattern was also observed for Ana tree mortality in the Khan River (r_S = 0.65, P = 0.08). There was no correlation between groundwater decline rates and tree mortality of Camel thorn and Mesquite trees.

Although tree mortality only correlated with decline rates for the Ana tree, the shape of the data produced for Mesquite trees correlations was similar, and therefore the data was used to build the tree mortality prediction model. Based on these observations, the proposed best model fit is semi-logarithmic ($y = \alpha \ln(x) + b$). The data fit the model in the case of Ana trees in the Swakop River (R^2 = 0.5, $F_{1,15}$ = 17.8, $P < 0.01$) and around production boreholes (R^2 = 0.3, $F_{1,6}$ = 4.7, P = 0.07). This was also true for Mesquite trees around production boreholes (R^2 = 0.5, $F_{1,5}$ = 7.0, P = 0.05). The slope of the line (0.05) for the log-transformed data (Fig. 10) is consistent for both Ana and Mesquite trees. We took the average of the constants for all three lines to derive a single average model that can be applied for both of these species.

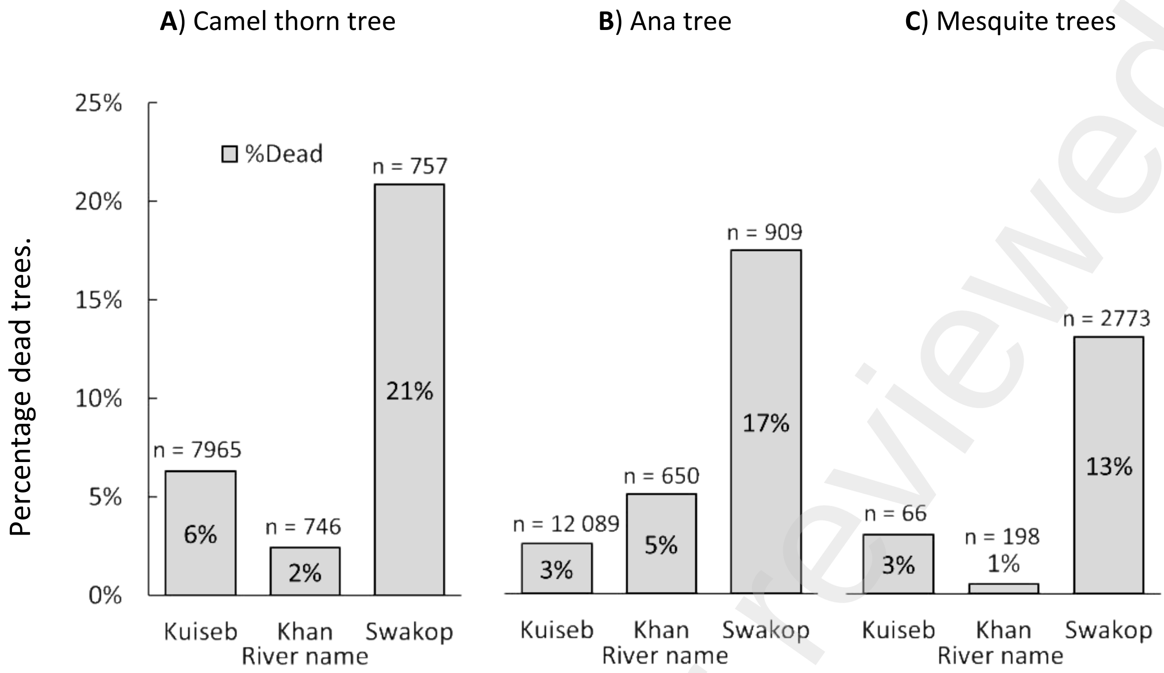


Figure 7. A comparison between the Kuiseb, Swakop and Khan rivers' tree mortalities calculated as a percentage number of dead trees out of the total number of trees for: A) Camel thorn, *B)* Ana, *C)* Mesquite trees. *The highest percentage tree mortality for all three tree species is observed in the Swakop River at 21%, 17% and 13% for Camel thorn, Ana and Mesquite trees respectively. In the other two rivers, the mortalities ranged between 1% and 6% across all species.*

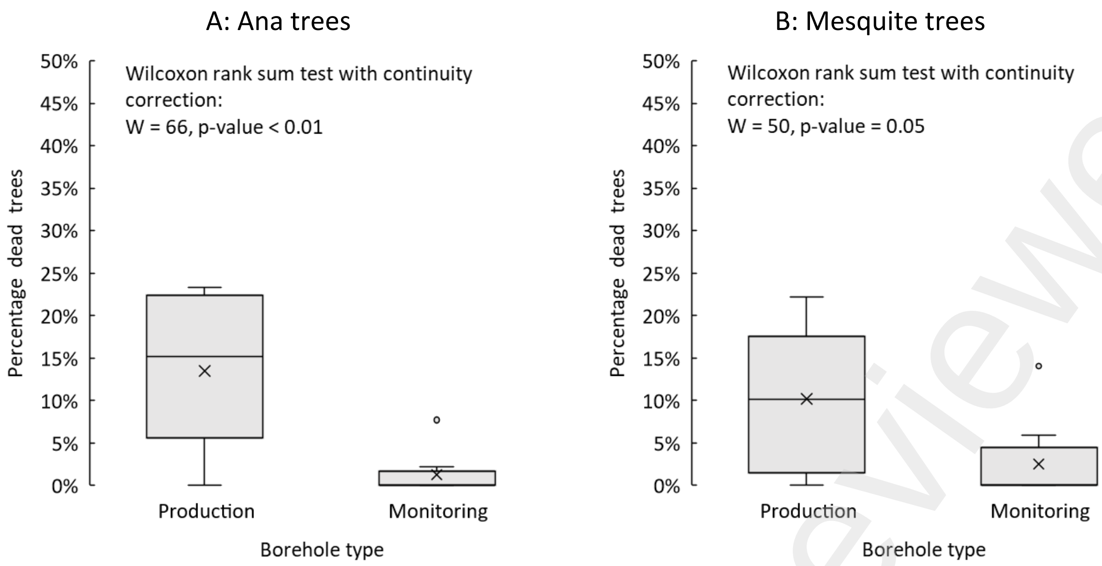


Figure 8. The difference between (A) Ana tree and (B) Mesquite tree mortalities around production versus monitoring boreholes. Tree mortalities were significantly higher around production boreholes for the Ana trees at 13.3% compared with 1% around monitoring boreholes (P < 0.01) and Mesquite trees at 10% compared with 2% around monitoring boreholes (P = 0.05). The monitoring borehole sample set was not normally distributed and therefore the Wilcoxon rank sum test was used to determine significance.

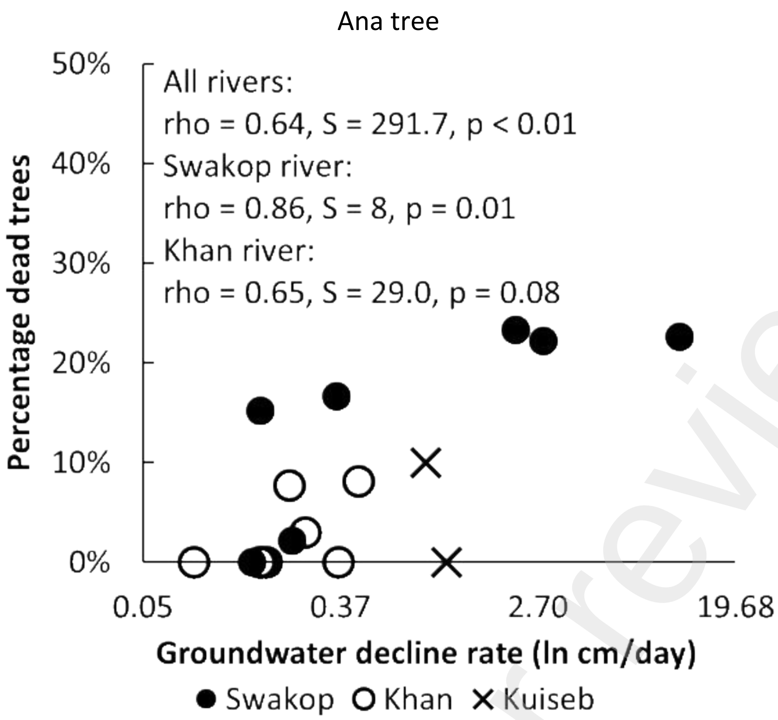


Figure 9. A correlation between the percentage dead ana trees within 4 km sections of river (2 km upstream and downstream from a borehole) and the mean of a subsample of 4 rates of groundwater decline from 1994 until 2015. Each black cross represents the mortality of trees within 2 km radius of a borehole in the Kuiseb River. Using data from all three rivers, tree mortality was correlated with groundwater decline rates where tree mortality increased as groundwater decline rates increased (r_S = 0.64, P < 0.01). Per river, this association was observed in the Swakop River (r_S = 0.86, P = 0.01) and to a lesser extent in the Khan River (r_S = 0.56, P = 0.08).

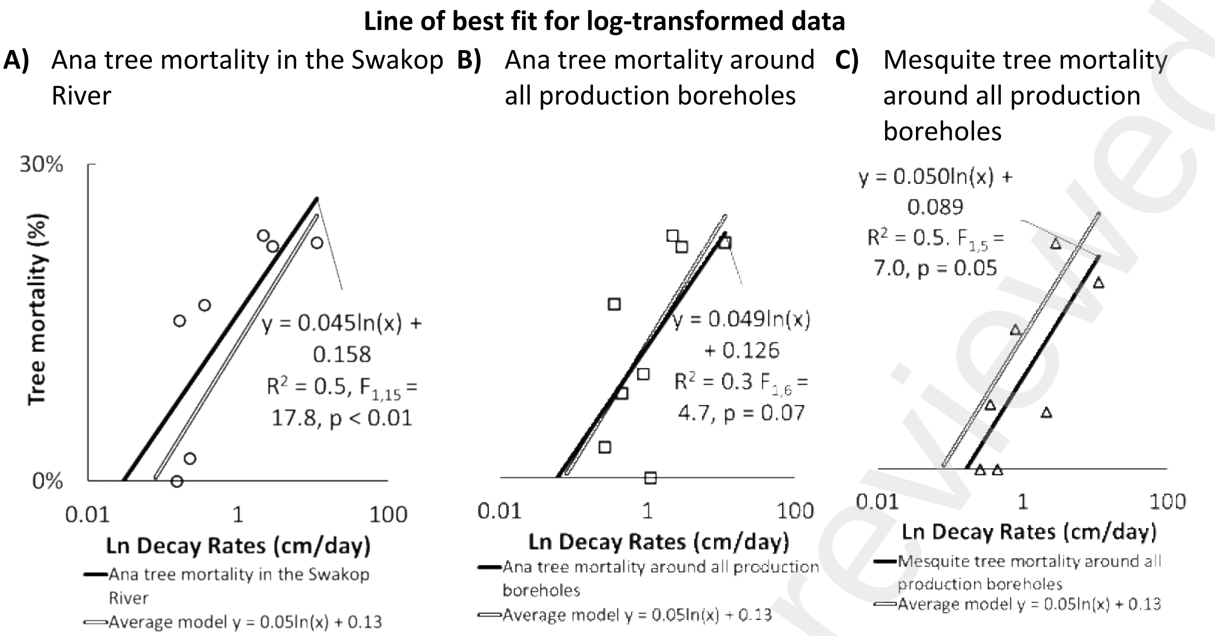


Figure 10. A summary for the proposed models representing the effect of groundwater decline rate on tree mortality. The average model (y = 0.05ln(x) + 0.13) was calculated from the line of best fit from three correlations: (A) Ana tree mortality in the Swakop River, (B) Ana tree mortality around all production boreholes and (C) Mesquite tree mortality around all production.

3.4 Data availability statement.

We have permission to use borehole data in our analysis, but not to share the raw data. Permission has been requested, but was not obtained at the time of the initial submission of this manuscript. We intend to upload all data, for which we have permission to share, to a database such as Mendeley Data when permission has been obtained from the respective data owners.

4 Discussion

Our study indicates that an increase in groundwater decline rates due to abstraction was very likely a driver of tree mortality in the study rivers. The differences that we recorded between tree mortality around production versus monitoring boreholes, and the correlation between groundwater decline rates and tree mortality, were key results. This is an important finding, because contrary to initial investigations (Mannheimer 2012), it suggests that these ephemeral river ecosystems are more sensitive to groundwater abstraction than was previously believed. The implication is that prevailing assumptions about phreatophyte rooting depth (Dennis *et al*. 2002) and the failure to account for groundwater decline rates may lead to flawed calculations of sustainable yield, which in turn fail to mitigate potential damage to ecosystems.

Our model suggests that any increase in abstraction rate could potentially increase tree mortality in these species. Abstraction that causes tree mortalities above the background rate should be avoided when possible and we use this tree mortality percentage to derive the decline rate limits. We expected background mortality to be represented by mortality rates around monitoring boreholes where evapotranspiration was the only driver of groundwater decline (0-2%). However, this value is probably an underestimate, because overall tree mortalities observed in the Khan and Kuiseb rivers were between 1 and 6%, and modelled mortality for ≈ 90% of monitoring borehole decline rates (0.08 and 0.23 cm day^{-1}) translated to between 3 and 7%. This is just below the decline rate described by Müller (2003) of 0.3 cm day^{-1} that led to canopy dieback in Ana trees in the Khan River.

Considering the arid nature of the study area, coupled with the proven impacts of other factors like diminished flood frequencies on tree establishment and survival (Douglas *et al*. 2016; 2018), and our on-site observations, we anticipate that even a modest rise in mortality to 10% could result in negative impacts to riparian woodlands. This could happen at a groundwater decline rate of as little as 0.5 cm day^{-1}. Thus, ideally abstraction should not increase groundwater decline rates of more than 0.2 cm day^{-1} to 0.23 cm day^{-1}. Where higher abstraction rates in the range between 0.23 and 0.5 cm day^{-1} are unavoidable, and must be maintained for long periods, we strongly recommend regular tree health monitoring with controls. We advise that management strategies should be in place to prevent excess tree mortality when tree health decline is observed and recommend against abstraction rates that lead to decline rates of greater than 0.5 cm day^{-1}.

Although the investigation of species-specific mortality in relation to groundwater decline rates was not the primary focus of this paper, it yielded interesting insights. Our findings suggest that groundwater decline rates might also influence shifts in the composition of the tree community and ecosystem dynamics with unknown consequences for the biodiversity and the dependent communities relying on the ecosystem services it offers.

We anticipated a correlation between mean groundwater depth and both tree density and mortality. However, shallower groundwater was associated with higher density only for mesquite trees. Despite its shallow groundwater levels, the highest tree mortality was observed in the highly-abstracted Swakop River, suggesting that tree mortality is driven by the groundwater decline rate rather than the absolute depth. Groundwater depths of up to 20 m b.g.l. (the deepest we observed) are probably all within the rooting depth of these species.

Differences in the impact of groundwater decline on tree mortality among the rivers may stem from variations in flood frequencies (Douglas *et al*. 2016; 2018), which are intricately tied to catchment management practices. While studies in the USA (Horton, Kolb & Hart 2001) showed that riparian forests in reservoir-managed rivers benefit by stabilised groundwater levels, this effect was absent in the study rivers. The Swakop River suffered a 32% reduction in surface discharge (BIWAC 2010) due to the construction of the Von Bach and Swakoppoort Dams within its upper catchments in the 1970s (Jacobson *et al*. 1995) and of the three study rivers, it had the highest tree mortality. The Khan and Kuiseb rivers do not have large dams within their upper catchments (Jacobson *et al*. 1995) and flood more frequently. Reduced flood frequencies in the Swakop River may have made trees more dependent on water in the aquifer and therefore more vulnerable to groundwater decline rates than the trees in the other two rivers. With projected climate change, annual precipitation is predicted to decrease, thus reduced flood frequencies are expected for all of Namibia's ephemeral rivers. Evapotranspiration is likewise predicted to increase (Dirkx *et al*. 2008), which will accelerate groundwater decline rates. All of these factors could increase tree mortality in all of Namibia's ephemeral rivers.

We had to use groundwater level values from a number of sources with unknown quality control procedures, and we could not confidently apportion error that might have originated from belowground hydrological structures. To address this, we used diverse grouping criteria and conducted analyses on several random sub-samples in an iterative fashion to establish correlations. Despite these constraints, the consistency in our results suggests that the modelled relationships between groundwater decline rates and mortality reflect real effects. This model provided valuable insights and reference values that can be used by management to adjust the sustainable yield so that the resultant ground water decline rate does not exceed the limits delineated in this study. The methods used here are applicable to any region, in which groundwater is used, to calibrate the sustainable yield to the sensitivity of any ecosystem. Given the increasing dependence on groundwater resources worldwide (Zektser & Everett 2004; Perrone 2020), this management tool is both relevant and necessary. Therefore, it should be considered good practise to monitor groundwater levels, phreatophyte health and mortality before and during active groundwater abstraction so that the impact of abstraction on riparian vegetation can be determined.

This study demonstrates that the groundwater decline rate, as well as other impacts on river hydrology such as reduced flood frequencies, must be considered when setting abstraction limits. The insights provided concerning the potential sensitivity of these three tree species to groundwater abstraction, and the groundwater decline rate limits determined here, will be valuable for Namibia's groundwater management authority. Moreover, this study underscores the importance to develop tree health monitoring protocols and proactive groundwater management strategies to ensure the sustainable utilisation of groundwater resources worldwide.

5 Acknowledgements

This project was conducted under the auspices of a research unit at Gobabeb dedicated to studying and monitoring the effects of mines on the Namib, with funding from the German-Namibian Technical Cooperation Project "Economic Geology" (a partnership between the German Federal Institute for Geosciences and Natural Resources, and the Geological Survey of Namibia), and Swakop Uranium (SU). We thank SU staff, particularly Ilka Shroër and Michelle Kilbourn-Louw, who provided quality-controlled borehole data and logistical support for fieldwork. Dr Mary Seely played a large role in kickstarting the monitoring programme in the ephemeral rivers when the Gobabeb Summer Development Programme of 2013 was dedicated to the first surveys. Several Gobabeb staff members, interns and students contributed their time and effort to data collection, with much of the work being led by Titus Shuuya.

6 Competing interests

Theo Wassenaar was a member of the consultant team appointed to conduct a legally mandated, independent Biodiversity Impact Assessment for Swakop Uranium's (SU) Husab Mine project. It was during this assessment that the need for the present study was recognized. The grant provided by SU for this study did not involve direct payments or salaries to any individual. The authors, therefore, have no competing interests to disclose.

7 Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT for spelling and grammar correction. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

8 References

Alley, W.M., Reilly, T.E. & Franke, O.L. (1999) Sustainability of Ground-Water Resources. U.S. Geological Survey Circular 1186. Government Printing Office, Denver, CO, U.S.A.

Bethune, S., Amakali, M., & Roberts, K. (2005) Review of Namibian legislation and policies pertinent to environmental flows. *Physics and Chemistry of the Earth*, **30**, 894–902.

BIWAC (2010) *Numerical Groundwater Model and Water Balance of the Swakop/Khan River System.* Windhoek, Namibia: Bittner Water Consult, GW1-2010-3-F.V.5.

Dean, W.R.J., Milton, S.J., & Jeltsch, F. (1999) Large trees, fertile islands, and birds in arid savanna. *Journal of Arid Environments*, **41**, 61–78.

Dennis, I., Van Tonder, G. & Reimann, K. (2002) *Risk based decision tool for managing and protecting groundwater resources*. University of the Free State, Bloemfontein, South Africa.

Dirkx, E., Hager, C., Tadross, M., Bethune, S. & Curtis, B. (2008) *Climate change vulnerability & adaptation assessment*. Ministry of Environment and Tourism, Windhoek, Namibia.

Dieckmann, U., Odendaal, W., Tarr, J.& Schreij, A. (2013) *Indigenous Peoples and Climate Change in Africa: Report on case studies of Namibia's Topnaar and Hai//om communities*. Legal Assistance Centre, Windhoek, Namibia.

Doody, T., Benger, S.N., Pritchard, J.L. & Overton, C. (2013). Ecological response of Eucalyptus camaldulensis (River Red Gum) to extended drought and flooding along the River Murray, South Australia, 1997-2011 and implications for environmental flow management. *Marine and Freshwater Research* [online]. Available from: https://doi.org/10.1071/MF13247 [Accessed 20 March 2022].

Douglas, C.M.S., Mulligan, M., Harrison, X. A., Henschel, J.R., Pettorelli, N. & Cowlishaw, G. (2016) Widespread dieback of riparian trees on a dammed ephemeral river and evidence of local mitigation by tributary flows. *PeerJ* [online], **4**, e2622. Available from: https://doi.org/10.7717/peerj.2622 [Accessed 15 June 2019].

Douglas, C.M.S., Cowlishaw, G., Harrison, X. A., Henschel, J.R., Pettorelli, N. & Mulligan, M. (2018) Identifying the determinants of tree distributions along a large ephemeral river. *Ecosphere*, **9**(6), e02223.

Heyns, P., Seely, M., Montgomery, S. & Pallet, J. (1998) *Namibia's water: A decisionmakers' guide*. Ministry of Agriculture, Water and Rural Development/Desert Research Foundation of Namibia, Windhoek, Namibia.

Horton, J.L., Kolb, T.E. & Hart, S.C. (2001) Physiological response to groundwater depth varies among species and with river flow regulation. *Ecological Applications*, **11**, 1046–1059.

Jacobson, P.J., Jacobson, K.N., & Seely, M.K. (1995) *Ephemeral rivers and their catchments: sustaining people and development in western Namibia.* Desert Research Foundation of Namibia, Windhoek, Namibia.

Kath, J., Reardon-Smith, K., Le Brocque, A.F., Dyer, F.J., Dafny, E., Fritz, L. & Batterham, M. (2014) Groundwater decline and tree change in floodplain landscapes: Identifying non-linear threshold responses in canopy condition. *Global Ecology and Conservation,* **2**, 148–160.

Mannheimer, C. (2012) *Possible causes of morbidity and mortality in Faidherbia albida in the Langer Heinrichberg compartment of the Swakop River (Central Namib Desert).* Unpublished report prepared for Langer Heinrich Uranium.

Mendelsohn, J., Jarvis, A., Roberts, C. & Robertson, T. (2002) *Atlas of Namibia: A Portrait of the Land and its People*. 1st edn. David Philip Publishers, Cape Town, South Africa:

Microsoft (2017) *Microsoft Excel.* [Software]. Redmond, WA: Microsoft Corporation [Accessed 14 May 2020].

MME (2010) *Strategic Environmental Assessment for the central Namib Uranium Rush*. Windhoek, Namibia: Ministry of Mines and Energy.

Müller, S. (2003) Effect of groundwater extraction on the vegetation in the Khan River at Rössing Uranium Mine, Namibia. *Namibia Scientific Society*, **51**, 17–31.

Müller, S. (2011) Central Namib – Windhoek Area. *Groundwater in Namibia an explanation to the Hydrogeological Map* (eds G. Christelis & W. Struckmeier), pp. 77-85. Ministry of Agriculture, Water and Rural Development, Windhoek, Namibia.

Pahl-Wostl, C., Arthington, A., Bogardi, J., Bunn, S. E., Hoff, H., Lebel, L., Nikitina, E., Palmer, M., Poff, L.N., Richards, K., Schlüter, M., Schulze, R., St-Hilaire, A., Tharme, R., Tockner, K., Tsegai, D. (2013) Environmental flows and water governance: managing sustainable water uses. *Current Opinion in Environmental Sustainability*, **5**, 341-351.

Perrone, D. (2020) Groundwater Overreliance Leaves Farmers and Households High and Dry. *One Earth*, **2**(3), 214-217, Available from: https://doi.org/10.1016/j.oneear.2020.03.001.

QGIS Development Team (2017) *QGIS Geographic Information System.* [Software]. Chicago: Open Source Geospatial Foundation. Available from: http://qgis.org [Accessed 25 February 2017].

R Core Team (2018) *R: A Language and Environment for Statistical Computing.* [Software]. Vienna: R Foundation for Statistical Computing. Available from: https://www.r-project.org [Accessed 13 March 2018].

Remmert, D. (2017) *Managing Windhoek's Water Crisis: Short-term Success vs Long-Term Uncertainty*. Windhoek, Namibia: Institute for Public Policy Research, 18.

Schachtschneider, K. (2010) *Water sourcing by riparian trees along ephemeral riverbeds*. PhD Thesis, University of Cape Town.

Schachtschneider, K. & February, E. (2013) Impact of Prosopis invasion on a keystone tree species in the Kalahari Desert. *Plant Ecology*, **214**, 597–605.

Shadwell, E., & February, E. (2017) Effects of groundwater abstraction on two keystone tree species in an arid savanna national park. *PeerJ* [online] **5**, e2923. Available from: https://doi.org/10.7717/peerj.2923 [Accessed 21 March 2017].

Strohbach, B., Ntesa, C., Kabajani, M., Shidolo, E. & D'alton, C. (2015) Prosopis encroachment along the Fish River at Gibeon, Namibia. I. Habitat preferences, population densities and the effect on the environment. *Dinteria*, **35**,53-73.

Stromberg, J.C., Tiller, R. & Richter, B. (1996) Effects of groundwater decline on riparian vegetation of semiarid regions: The San Pedro. Arizona. *Ecological Applications*, **6**, 113–131

Van Vuuren, O. (2012) *Groundwater: a Namibian Perspective.* Publisher: Unknown.

Wang, L., Jiao, W., MacBean, N., Rulli, M.C., Manzoni, S., Vico, G. & D'Odorico, P. (2022) Dryland productivity under a changing climate. *Nature Climate Change*, **12**, 981–994.

Wanke, H., Nakwafila, A., Hamutoko, J.T., Lohe, C., Neumbo, F., Petrus, I., David, A., Beukes, H., Masule, N. & Quinger, M. (2014) Hand dug wells in Namibia: An underestimated water source or a threat to human health? *Physics and Chemistry of the Earth*, **76–78**, 104–113. Available from: https://doi:10.1016/j.pce.2015.01.004 [Accessed 06 March 2020].

Ward, J.D. & Breen, C.M. (1983) Drought Stress and the Demise of Acacia albida along the Lower Kuiseb River, Central Namib Desert: Preliminary Findings. *South African Journal of Science*, **79**, 444–447.

Zektser, I.S. & Everett, L.G. (2004) *Groundwater resources of the world and their use*. United Nations, Paris.