Hydrological Niche of Restionaceae Species in Silvermine South Africa

Danni Guo[*1], Guy F. Midgley[2], James Ayuk[3], Charles F. Musil[1]

[*1]Biodiversity Research Assessment and Monitoring, South African National Biodiversity Institute, Kirstenbosch Research Center, Private Bag X7, Claremont 7735, South Africa

[2]Department of Botany and Zoology, Stellenbosch University, Private Bag X1, Matieland 7602, Cape Town, South Africa

[3]Department of Biodiversity and Conservation Biology, Faculty of Natural Sciences, University of the Western Cape, Private Bag X17, Bellville 7535, South Africa

[*1]d.guo@sanbi.org.za; [2]gfmidgley@sun.ac.za; [3]jaayuk@gmail.com; [4]cfmusil@gmail.com

***Abstract*-The Restionaceae species of the fynbos biome is part of the Cape floral kingdom, one of only six floristic kingdoms in the world. It is threatened by urbanization, agricultural expansion and groundwater extraction. Therefore, it is necessary to assess and monitor the Restionaceae species. South Africa is a semi-arid environment and hydrological factors are the main variables in the determination of species niches. This study investiagates the microclimate at Silvermine, and examines the contribution of hydrological variables to plant species distribution, thus creating a hydrological niche. This study generates its own unique microclimate hydrological datasets for modelling species niche. Additionally, this study assessed and modelled the effectiveness of the use of hydrological variables to determine species hydrological niche, at a microclimate level in a semi-arid environment. It also provided evidence regarding the importance of the study to conservation and future climate change impact analysis of plant species and species richness.**

Keywords- Hydrological Niche; Restionaceae; Fynbos Biome; Microclimate; Silvermine; South Africa

I. INTRODUCTION AND BACKGROUND

The Cape floral kingdom is one of only six floristic kingdoms in the world, and is the smallest and richest per unit of area. Fynbos consists of natural shrubland vegetation and forms part of the Cape floral kingdom, which contains 80% of the Cape Floristic Region's species [1]. Fynbos is a key vegetation community, and is composed of the plant families Ericaceae, Proteaceae and Restionaceae. The Restionaceae are a family of perennial evergreen wind-pollinated flowering plants, which vary from 10 cm to 3 m in height which, based on evidence from fossil pollens, originated more than 65 million years ago [1]. In terms of conservation, the Restionaceae is threatened by urbanization, agricultural expansion and groundwater extraction. Therefore, it is very important to discover the influence of hydrological variables on the Restionaceae at a local microclimate level, particularly for conservation and climate change. Due to the semi-arid environment of South Africa, hydrological factors are major environmental variables which contribute to the determination of species niche. A niche defines the way in which a species fits into an ecological community or ecosystem, and is modelled by environmental variables [2]. In this study, we examine the hydrological niche, which models the Restionaceae habitat through hydrological variables.

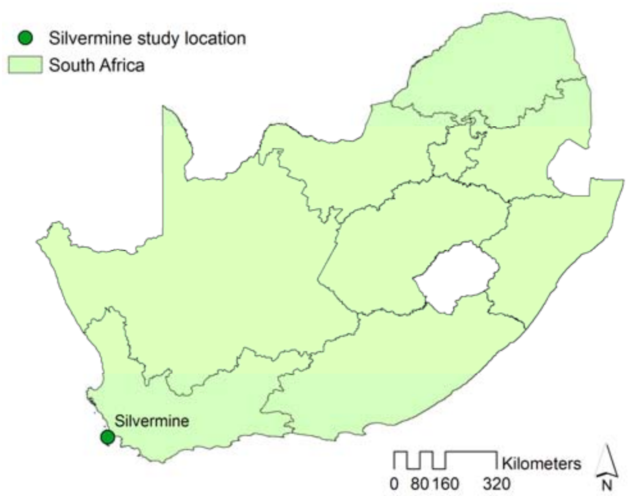

Fig. 1 Silvermine study location in South Africa

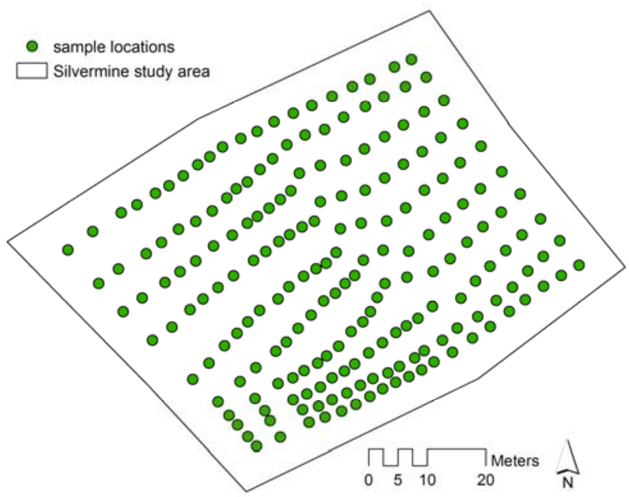

Fig. 2 Silvermine study area plot and sample locations

The study area, as shown in Fig. 1, is at Silvermine, within the Cape Floristic Region. Fig. 2 shows a plot of the 50m by 50m study area, with 200 sample locations, placed on a grid 3-5 m apart. It must be noted that the precise plot area size varies

DOI: 10.5963/JWRHE0403011

with the land topography of the study area. Samples measurements were taken for the following variables: elevation, water table depth, soil drying threshold, waterlogging threshold, and for the presence or absence of Restionaceae species at each sample point [3]. Previous studies of species niche have focused on macroclimate level and climate variables rather than local microclimate level and hydrological variables. Primarily, previous studies of species niche and climate change have used country-wide macroclimate datasets.

The soil water regime of hydrological variables used in the study is based on the hydrological models from previous research [4]. The water-table depth was monitored by the use of tube wells, and supported by automatic logging pressure transducers. The tube wells were read manually every two weeks, and subsample data was recorded every four hours for at least twelve months. Using the hydrological data from the tube wells, the water-table depth for each sample location was obtained [3, 5, 6]. The water-table depths were then used to calculate the sum exceedance values (SEVs) for aeration and water stress [7].

The sum exceedance value (SEV) is a scale used to measure the exposure of plants to aeration or drought stress when the water table falls below average (causing drought), or rises above averate (causing aeration stress) [8]. The SEVs are a derivation of water table depth and the duration of flooding or drying. Poor soil corrosions are caused by water logging, and drought stress is caused by soil dryness [9]. The soil drying threshold (SEVd) is calculated according to the water-table depth which provides 50 cm (5 kPa) of tension at the soil surface, where the plants show the effects of water stress [10]. The SEVa threshold is calculated as the water-table depth at which the densest rooting, located at a depth of 0-100 mm, becomes waterlogged, or when the air-filled pore space is less than 10% of the total soil volume [11]. The SEV represents the degree to which water-tables exceed the thresholds, and the extent of the exceedance is then cumulated to obtain the SEV. For soil, the drying threshold is between 45-48 cm, and the aeration stress threshold is 15-20 cm [3, 5, 6].

This study generated its own unique microclimate hydrological datasets for modelling species niche. It focuses on the microclimate level, and examines the influence of hydrological variables on plant species distribution, creating a hydrological niche. This primary objective of this study is to assess and model the effectiveness of using hydrological variables to determine species hydrological niche at a microclimate level in a semi-arid environment, and to provide evidence of the importance of the study to conservation and future climate change impact analysis.

II. RESTIONACEAE AND HYDROLOGICAL VARIABLES

To explore the hydrological niche of plant species, the hydrological variables to be evaluated are the water table depth, soil drying threshold, waterlogging threshold, and the relative elevation. This study generated its own microclimate hydrological datasets for modelling species niche, based on the aforementioned variables. Samples were taken at each sample point to determine the presence or absence of Restionaceae species [3]. The five Restionaceae plant species (Fig. 3) found at the Silvermine study area are: Elegia filacea, Hypodiscus aristatus, Restio capensis, Restio cincinnatus, and staberoha cernua.

Elegia filacea Hypodiscus aristatus Restio capensis Restio cincinnatus Staberoha cernua

Fig. 3 Five Restionaceae plant species found at Silvermine [12]

Ordinary kriging was conducted on the hydrological data in order to provide the microclimate environmental layers used to calculate the hydrological niche of the species. Kriging is an interpolation procedure which uses collected observations and a semivariogram to determine the values of non-sampled locations; the procedures involved in kriging incorporate measures of error and uncertainty when determining estimations. Ordinary kriging is a type of kriging that uses a location-dependent weighted average of the observed values colleted from the given locations, where the weights depend upon the spatial correlation structure of the data [13, 14, 15].

Ordinary kriging is a linear predictor [13, 14, 15]:

DOI: 10.5963/JWRHE0403011

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \tag{1}$$

Where s_i is a location with observation $Z(s_i)$, and coefficient λ_i satisfies the ordinary kriging linear equation system:

$$\begin{cases} \sum_{j=1}^{N} \lambda_j \gamma\left(\varepsilon(s_i) - \varepsilon(s_j)\right) - \psi = -\gamma\left(\varepsilon(s_i) - \varepsilon(s_0)\right),\ i = 1, 2, \cdots, N \\ \sum_{j=1}^{N} \lambda_j = 1 \end{cases} \tag{2}$$

The ordinary kriging system is generated under the assumption of an additive spatial model:

$$Z(s) = \mu(s) + \varepsilon(s) \tag{3}$$

Where $\mu(s)$ is the basic (expected) spatial trend and $\varepsilon(s)$ is an error term

$$\mathrm{E}\left[\varepsilon(s)\right] = 0, \mathrm{V}\left[\varepsilon(s)\right] = \sigma^2(s) \tag{4}$$

Accordingly, the variogram 2γ of the random error function ε is defined as follows:

$$2\gamma(h) = \mathrm{E}\left[\left(\varepsilon(s+h) - s(h)\right)^2\right] \tag{5}$$

Where h is the separate vector between two spatial points $s+h$ and s [13, 14, 15]. The semi-vario gram model used in this study is as follows:

$$\gamma(\mathrm{h};\theta) = \theta_s\left[1 - \exp\left(-3\left(\frac{\|\mathrm{h}\|}{\theta_r}\right)^{\theta_e}\right)\right] \tag{6}$$

for all h, where $\theta_s \geq 0$ and $0 \leq \theta_e \leq 2$ [16]. Thus, the microclimate variables are generated.

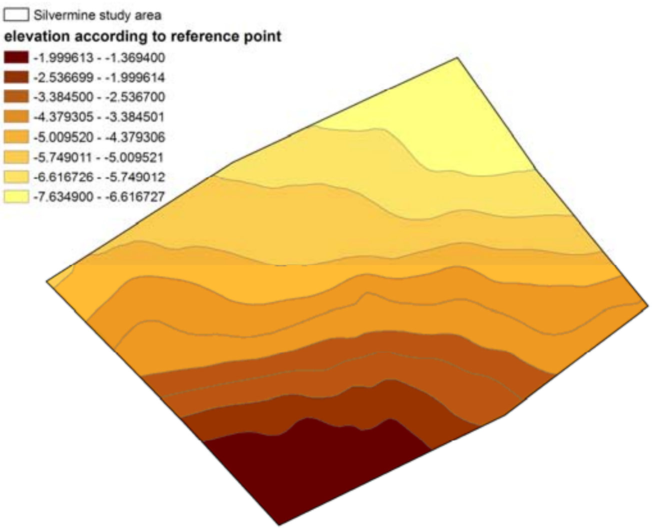

Fig. 4 Relative elevation according to reference point, longitude 18.44835, latitude -34.10925 at 378 meters

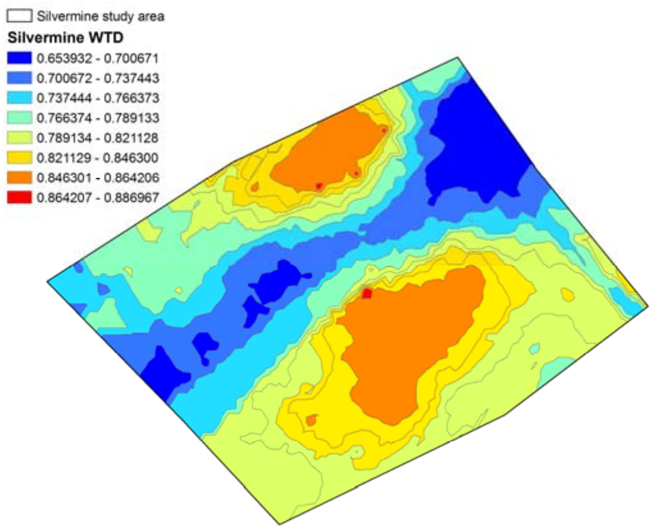

Fig. 5 Water table depth (WTD) at Silvermine

Fig. 4 shows the relative elevation. These values were recorded in relation to a reference point near the plot: longitude 18.44835, latitude -34.10925 at 378 meters. The reference point at the Silvermine location was at a higher elevation than the plot, so all points on the plot appeared negative; he darker colours indicate higher relative elevations. In Fig. 5, the water table depth (WTD), sometimes referred to as depth to water (DTW), is shown. Higher WTD values signify deep or lower water tables, which are related to drier conditions.

DOI: 10.5963/JWRHE0403011

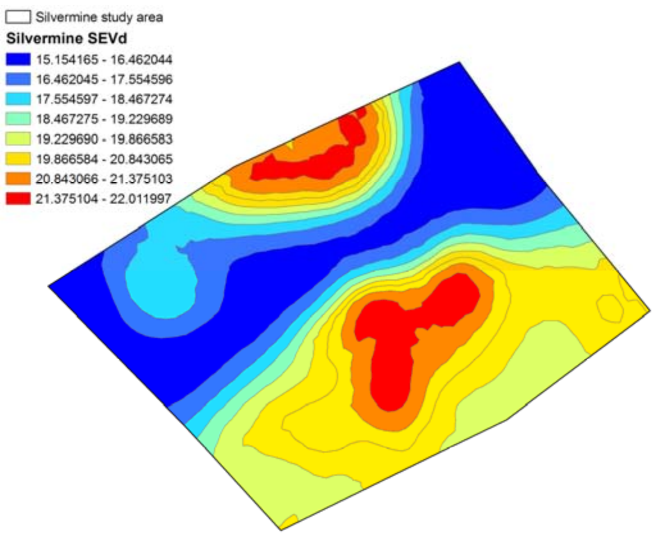

Fig. 6 Soil drying threshold (SEVd) at Silvermine

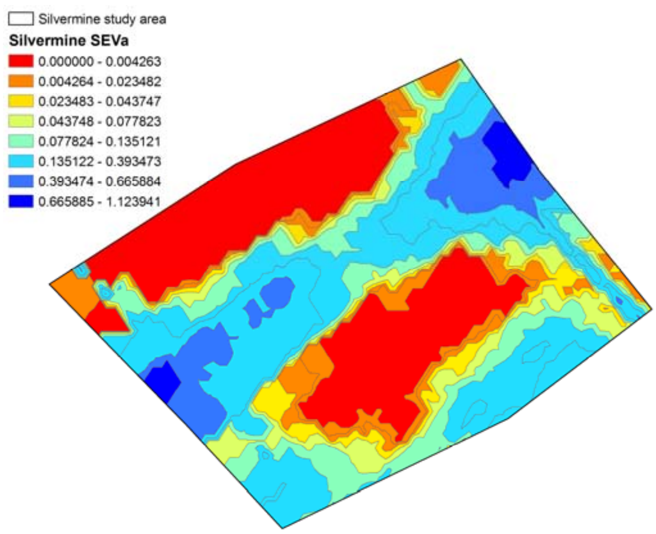

Fig. 7 Soil aeration stress or waterlogging threshold (SEVa) at Silvermine

The soil drying threshold (SEVd) is displayed in Fig. 6. A sum exceedence value for soil drying is cumulated during periods in which the moisture tension of the surface soil exceeds 5 kPa, which could potentially induce stomatal closure in plants [9]; high SEVd indicates dry soil conditions. The soil aeration stress or waterlogging threshold (SEVa) is shown in Fig. 7. A sum exceedance value for aeration is calculated from the cumulative periods in which the air-filled porosity of the soil falls below 10% by volume, which is assumed to preclude the free diffusion of oxygen in the topsoil [9]; high SEVa indicates wet conditions in the soil.

III. HYDROLOGICAL NICHE MODELLING

Restionaceae occupy a wide range of environmental conditions, and inhabit both moist and dry environmental conditions [3]. Therefore, the five species used in the study have different hydrological preferences; some are distributed in wetter environment and some are distributed in drier environment. In order to examine the distribution and the relationship between the species and hydrological variables, species distributions have been modelled to show the hydrological niches of the five studied species. Species distribution models are used to estimate the relationship between Restionaceae species records at sample sites, as well as the environmental and spatial characteristics of the sites [17]. The species distribution model used in this study is achieved by MaxEnt [18].

MaxEnt applies Bayesian methods to estimate the potential geographic distribution of species by finding the probability distribution of maximum entropy; it is an effective method for modelling species distributions from presence-only data (Elith et al. 2011). The conventional Bayesian risk analysis is based on the quadratic loss function and the use of a conjugate family. Maximum entropy modelling is an important Bayesian inference, which is established by different risk criteria. MaxEnt is a Bayesian approach by which the species probability distribution is statistically estimated by searching the family of probability distributions under the maximum entropy criteria subject to environmental constraints.

The Gibbs family $\{q_\lambda(x), \lambda \in L\}$ is expressed as follows:

$$q_\lambda(x) = \frac{1}{Z_\lambda(x)} \exp\left(\sum_{i=1}^{m} \lambda_i f_i(x)\right) \tag{7}$$

Where $\lambda_i = (\lambda_1, \lambda_2, ..., \lambda_m)$ is the weight vector, λ_i represents the weight parameter, L is the m-dimensional space, $f_i(x)$ represents the probability distribution of species i, and $Z_\lambda(x)$ is the normalized constant. Note that each element x is a pixel in the investigated area. The probabilities $f_i(x)$ represent the relative suitability of the environmental conditions in each pixel [18, 19, 20].

Fig. 8 depicts the hydrological niche of the Elegia filacea species, modelled using hydrological variables. The percentage contribution of each variable to Elegia filacea species distribution is as follows: elevation (19.5%), WTD (50.5%), SEVd (23.1%), SEVa (6.8%). The preferred relative elevation is between -5 and -4, water table depth is 0.62 to 0.72, and soil drying threshold is 14 to 18. Fig. 9 shows the hydrological niche of the Hypodiscus aristatus species, modelled using hydrological variables. The percentage contribution of each variable to the Hypodiscus aristatus species distribution is as follows: elevation (47.2%), WTD (28.6%), SEVd (9.3%), SEVa (14.8%). The preferred relative elevation is between -5 and -3, and water table depth is 0.86 to 0.9.

DOI: 10.5963/JWRHE0403011

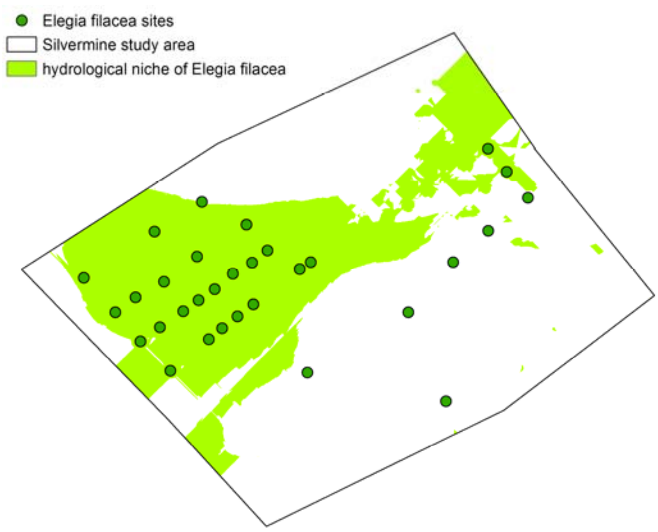

Fig. 8 Elegia filacea species hydrological niche

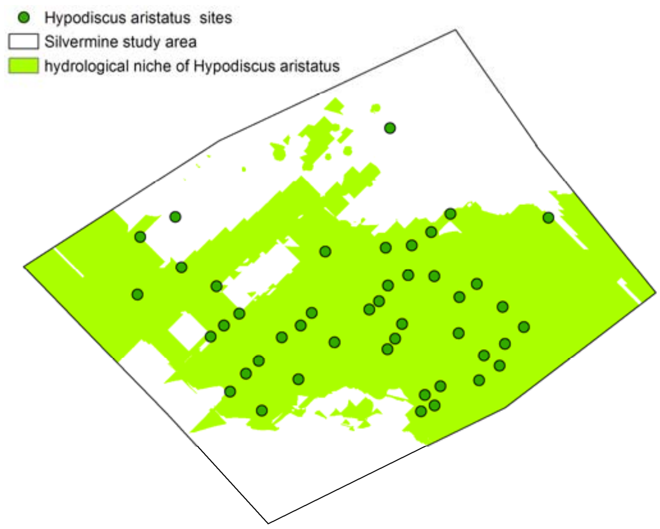

Fig. 9 Hypodiscus aristatus species hydrological niche

Fig. 10 shows the hydrological niche of the Restio capensis species, modelled according to hydrological variables. The percentage contribution of each variable to Restio capensis species distribution is as follows: elevation (36.5%), WTD (36.9%), SEVd (1.6%), SEVa (24.9%). The preferred relative elevation is between -6 and -1, water table depth is 0.86 to 0.9, and waterlogging threshold -0.1 to 0.5. As shown in Fig. 11, the hydrological niche of the Restio cincinnatus species is modelled using hydrological variables. The percentage contribution of each variable to Restio cincinnatus species distribution is as follows: elevation (4.3%), WTD (62.1%), SEVd (10.1%), SEVa (23.4%). The preference for water table depth is 0.6 to 0.7 and 0.8 to 0.9, and the waterloging threshold is -0.1 to 0.65. As seen from the niche map above, this species adapts itself to a wide variety of environmental and hydrological conditions.

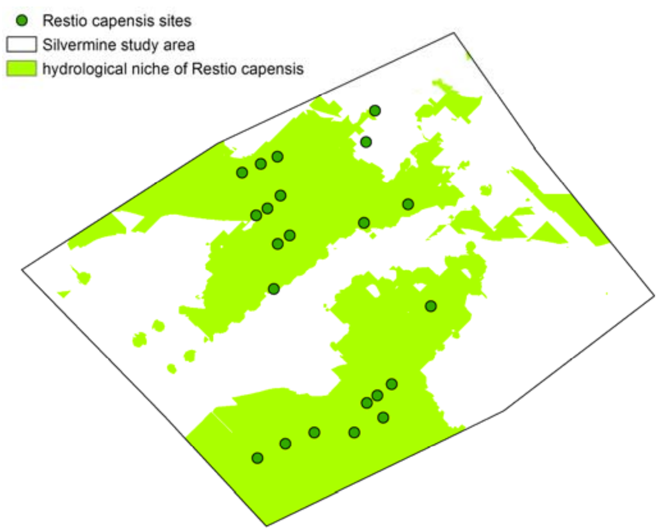

Fig. 10 Restio capensis species hydrological niche

Fig. 11 Restio cincinnatus species hydrological niche

As shown in Fig. 12, the hydrological niche of the Staberoha cernua species is modelled using hydrological variables. The percentage contribution of variables to staberoha cernua species distribution is as follows: elevation (19.9%), WTD (73.1%), SEVd (0%), SEVa (7%). The preferred relative elevation is between -6 and -1, and water table depth is 0.62 to 0.75.

DOI: 10.5963/JWRHE0403011

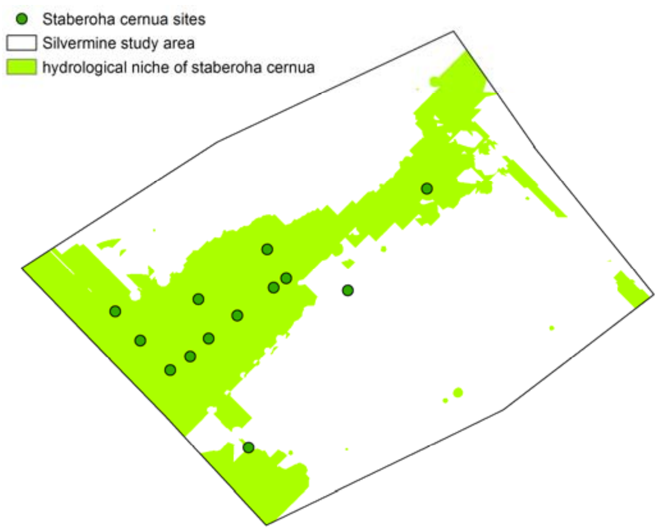

Fig. 12 Staberoha cernua species hydrological niche

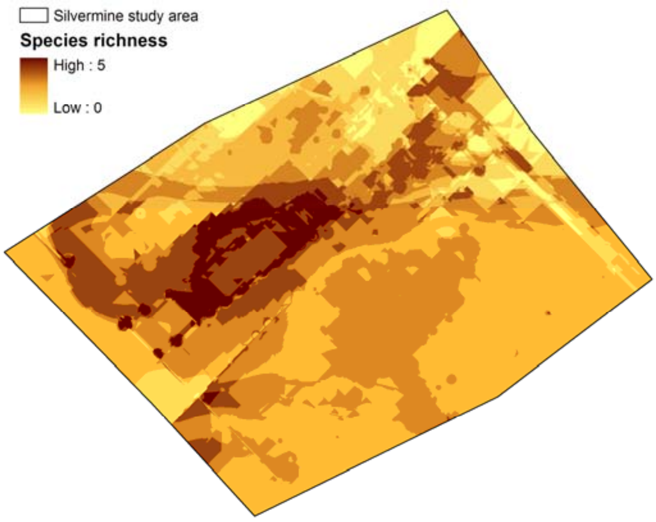

Fig. 13 Species richness map of Silvermine study area

As shown in Fig. 8-12, some Restionaceae species prefer wetter conditions and some prefer drier conidtions, while Restio cincinnatus prefers a wide range of hydrological conditions. Each individual species has its own hydrological niche with their own niche requirements, but they also coexist with other species within the same ecological niche, and thus compete for the same hydrological resources.

TABLE 1 PERCENTAGE CONTRIBUTION OF THE ENVIRONMENTAL VARIABLES TO SPECIES DISTRIBUTIONS

Species	Elevation	WTD	SEVd	SEVa
Elegia filacea	19.5	50.5	23.1	6.8
Hypodiscus aristatus	47.2	28.6	9.3	14.8
Restio capensis	36.5	36.9	1.6	24.9
Restio cincinnatus	4.3	62.1	10.1	23.4
Staberoha cernua	19.9	73.1	0	7

Table 1 identifies the important contributions that each hydrological variable makes to each of the five species. The water table depth is identified as the main variable of influence, and is important to all five species. The soil dryness threshold and waterloging threshold are both correlative and dependent on the water table depth. This indicates that should there be any climate change which results in changes of water table depth it would impact the species niches and might cause changes in species distribution.

Fig. 13 depicts the species richness of the Restionaceae species. The map shows that high species richness is correlated to low water table depth, a low soil drying threshold, and a high waterloging threshold. This indicates that the species richness index is higher in regions with wetter soil conditions. These study results suggest a direct impact on the conservation of species richness. Should there be any climate change (for example, less rainfall) resulting in a higher water table depth, it could result in a reduction of species richness, as some species might not survive with the changed conditions. Accounting for South Africa’s semi-arid environment, urbanization, groundwater extraction and the creation of more bore holes will ultimately cause a change in hydrology and therefore impact the Restionaceae species niche [21, 22].

IV. CONCLUSIONS

In this study, we employed microclimate modelling techniques to generate hydrological layers, in order to explore the hydrological niche of the Restionaceae species. In the Silvermine study area, the water table depth was identified as the main contributing variable, and important to all five studied species. Relative elevation, waterloging threshold, and soil dryness threshold all contribute differently to the five species: Elegia filacea, Hypodiscus aristatus, Restio capensis, Restio cincinnatus, and staberoha cernua. This indicates the different hydrological requirements of each individual species, all of which yet coexist and share the same hydrological niche area in Silvermine.

The study assessed and modelled the effectiveness of using hydrological variables to determine hydrological niches, at a microclimate level in a semi-arid environment. The study has also provided evidence of the importance of studied variables to conservation and future climate change impact analysis, because any changes in the hydrological variables will cause changes in the hydrological niche and a subsequent change in the species richness index. The results of this study are invaluable to the

DOI: 10.5963/JWRHE0403011

assessment and monitoring of plant species due to hydrological changes.

ACKNOWLEDGMENTS

We would like to thank Yoseph N. Araya and Jonathan Silver town of the Open University UK for their pioneering work of hydrological niche in plant communities in the Fynbos biome. The species and hydrological data used in this study was collected using grants from the Leverhulme Trust and the Darwin Initiative (Defra), and using South African National Biodiversity Institute (SANBI) resources. This work was financially supported in part by the National Research Foundation (NRF) Funding Reference: IFR150206113775 Grant number: 96163.

REFERENCES

[1] Wikipedia. (2015) Fynbos. Restionaceae. [Online]. Accessed: 04-05-2015. Available: http://en.wikipedia.org/.

[2] Moyle, P. (2012) Niche and habitat. Marine Conservation. [Online]. Accessed: 20-04-2012. Available: http://marinebio.org/Oceans/Conservation/Moyle/ch7.asp.

[3] Y. N. Araya, J. Silvertown, D. J. Gowing, K. J. McConway, H. P. Linder, and G. F. Midgley, "A fundamental, eco-hydrological basis for niche segregation in plant communities," *New Phytologist*, vol. 189, pp. 253-258, 2011.

[4] D. J. Gowing and E. G. Youngs, "The effect of the hydrology of a thames flood meadow on its vegetation," *British Hydrological Society Occasional Paper*, vol. 8, pp. 69-80, 1997.

[5] Y. N. Araya, J. Silvertown, D. J. Gowing, K. J. McConway, H. P. Linder, and G. F. Midgley, "Do niche-structured plant communities exhibit phylogenetic conservatism? A test case in an endemic clade," *Journal of Ecology*, vol. 100, pp. 1434-1439, 2012.

[6] J. Silvertown, Y. N. Araya, and D. J. Gowing, "Hydrological niches in terrestrial plant communities: A review," *Journal of Ecology*, vol. 103, iss. 1, pp. 93-108, 2014.

[7] D. J. Gowing and G. Spoor, "The effect of water table depth on the distribution of plant species in lowland wet grassland," in UK floodplains, R. Bailey, P. Jose, B. Sherwood, Ed. Otley, UK: Westbury, pp. 185-196, 1998.

[8] J. Silvertown, "Plant coexistence and the niche," *Trends in Ecology and Evolution*, vol. 19, pp. 605-611, 2004.

[9] J. Silvertown, M. E. Dodd, D. J. Gowing, and J. O. Mountford, "Hydrologically defined niches reveal a basis for species richness in plant communities," *Nature*, vol. 400, pp. 61-63, 1999.

[10] I. E. Henson,C. R. Jenson, and N. C. Turner, "Leaf gas exchange and water relations of lupins and wheat. I. Shoot responses to soil water deficits," *Australian Journal of Plant Physiology*, vol. 16, 401-413, 1989.

[11] K. B. Higgins, A. J. Lamb, and B. W. van Wilgen, "Root systems of selected plant species in mesic mountain fynbos in the Jonkershoek valley, southwestern cape province," South African Journal of Botany, vol. 53, pp. 249-257, 1987.

[12] iSpot. (2015) Species Dictionary. The Open University. [Online]. Accessed: 04-05-2015. Available: http://www.ispotnature.org/species-dictionaries/sanbi.

[13] D. Guo, R. Guo, and C. Thiart, "Predicting Air Pollution Using Fuzzy Membership Grade Kriging," *Journal of Computers, Environment and Urban Systems*, vol. 31, iss. 1, pp. 33-51, 2007.

[14] D. Guo, R. Guo, C. Thiart, and T. Oyana, "GM(1,1)-Kriging Prediction of Soil Dioxin Pattern," in Representing, Modeling and Visualizing the Natural Environment: Innovations in GIS 13, N. J. Mount, G. L. Harvey, P. Aplin, G. Priestnall, Ed. Florida: CRC Press, Taylor & Francis Group, pp. 243-253, 2009.

[15] D. Guo, R. Guo, C. Thiart, and Y. H. Cui, "Imprecise Uncertainty Modelling of Air Pollutant PM10," in Advanced Air Pollution, F. Nejadkoorki, Ed. InTech, Open Access Publisher, pp. 193-212, 2011.

[16] Environmental Systems Research Institute (ESRI), Using ArcGIS Geostatistical Analyst, Redlands, USA: Environmental Systems Research Institute, 2001.

[17] J. Franklin, Mapping species distributions: spatial inference and prediction, Cambridge, UK: Cambridge University Press, 2009.

[18] S. J. Phillips, R. P. Anderson, and R. E. Schapire, "Maximum entropy modeling of species geographic distributions," *Ecological Modelling*, vol. 190, pp. 231-259, 2006.

[19] J. Elith, S. J. Phillips, T. Hastie, M. Dudík, Y. E. Chee, and C. J. Yates, "A statistical explanation of MaxEnt for ecologists," *Diversity and Distributions*, vol. 17, pp. 43-57, 2011.

[20] S. J. Phillips, M. Dudík, and R. E. Schapire, "A maximum entropy approach to species distribution modeling," in Proc. of the 21st International Conference on Machine Learning, 2004, pp. 655-662.

[21] M. Kuhlmann, D. Guo, R. Veldtman, and J. Donaldson, "Consequences of warming up a hotspot: Species range shifts within a centre of bee diversity," *Diversity and Distributions*, vol. 18, iss. 9, pp. 885–-897, 2012.

[22] M. McLeish, D. Guo, S. van Noort, and G. F. Midgley, "Life on the edge: rare and restricted episodes of a pan-tropical mutualism adapting to drier climates," *New Phytologist*, vol. 191, iss. 1, pp. 210-222, 2011.

DOI: 10.5963/JWRHE0403011