Research article

Long-Term Hydrologic Trend Analysis of the Diamphwe River Basin in Central Malawi

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Abstract Extreme weather events in developing countries can cause economic consequences, livelihood losses, and increased financial and societal costs. Identifying these events is often accomplished through trend analysis of historical climatic and hydrologic data. This study focused on the Diamphwe River basin in central Malawi. The Diamphwe River basin is a vital region supporting wetlands, ecosystems, agriculture, and water supplies, as well as irrigation for winter vegetable cropping for the Dedza and Lilongwe districts. Over 90 percent of local households earn their livelihood through rain-fed reliant farming. Long-term hydrologic trends were analyzed for the region, which is essential for managing and improving its agricultural productivity. Mann-Kendall and Pettit trend tests were conducted using 1975 to 2010 rainfall and river discharge data generated by R software and XLSTAT. The research revealed long-term trends of decreasing rainfall and river discharge, with 1988 as a transition year for the decreasing trends of the parameters in the basin. We also found that there was trend consistency within each month. Both rainy season and dry season months showed decreasing within months trends of the two parameters. Further, the river discharge fluctuation was significant in November and December, when the dry season changes to the rainy season, and in April, when the rainy season changes to the dry season. To sustain rainfed agriculture and introduce irrigated agriculture, it is suggested that water use planning should be based on the assumption that rainfall and river discharge will gradually decrease in/over what time frame? And that river flow fluctuations will become more significant and impactful in November, December, and April.

Keywords climate change, trends, river discharge, rainfall, Mann-Kendall test, Pettitt test

INTRODUCTION

According to the UN Food and Agriculture Organization (FAO), the world's population is expected to be 9.1 billion by 2050 (FAO, 2009). Irrigation development will be necessary to increase and maintain sufficient food production, especially in Africa, due to its combination of projected population gain and relative insufficiency of water. The FAO advocates climate-smart agriculture

(CSA), which requires the promotion of agriculture with enhanced adaptability to climate change (FAO, 2013). Some examples of CSA include vermicompost and mineral water applications to improve plant growth parameters (Saiyakit and Boonthai Iwai, 2022), reduced-tillage cultivation, crop leftovers and cover crops to keep farmland covered and rotating of crops. Additionally, the use of drip irrigation is key to equitable and economical water distribution in areas with water scarcity (Muhammad Zaharaddeen et al., 2023). Analysis of long-term changes in rainfall and river discharge is necessary to develop irrigation plans that adopt CSA and minimize the impact of climate change. A thorough analysis of hydroclimatic parameter trends, for example, by measuring rainfall at the watershed level using Mann-Kendall and Pettitt tests, can help predict potential hazards (Sayemuzzaman and Jha, 2014). Further, Barua et al. (2013), argue that analyzing local hydroclimatic variables is essential to understand and react to climate change's impact on a specific area. Studying river discharge changes and weather patterns is essential to improve ecological sustainability and agricultural production, noted Klavins et al. (2014) and Langat et al. (2017).

Climate change can affect the rain cycle by altering its processes (Pervez and Henebry, 2015). Stream flow is sometimes affected by its nature, either gaining or losing stream (Spellman and Drinan, 2001). If droughts are common in an area, the rivers are directly affected. Over the 20th century, sub-Saharan Africa experienced more El Nino periods with below-normal rainfall, versus La Nina periods of above-normal rainfall. (Gommes, 1996; Ngongondo, 2005).

Hydrologically, Malawi is divided into 17 Water Resource Areas (WRAs) covering 94,000 km². The Diamphwe River in WRA 4 relies on overland flow and can run dry during low rainfall (Kelly et al., 2020). The Diamphwe River basin is an essential watershed for food production in Malawi, where agricultural productivity can also be improved by increasing adaptability to climate change (Malawi Government, 2019). However, long-term hydrological research on rainfall and river discharge trends has not been conducted despite its socio-economic importance to the Lilongwe and Dedza districts. This research, therefore, intends to determine how long-term trends of the two hydrologic parameters (rainfall and river discharge) affect agricultural and water use activities in the river basin.

MATERIALS AND METHODS

Study Site

Figure 1 demonstrates the location of the Diamphwe River basin which spans over 1,390.92 km^2 and originates from the Dzalanyama mountains, joining the Linthipe River at the discharge gauge station (34.0886°E 14.1345°S). The total river length is 82.76 km. In central Malawi, the river borders the Lilongwe and Dedza districts (Banda et al., 2019; Munthali et al., 2022).

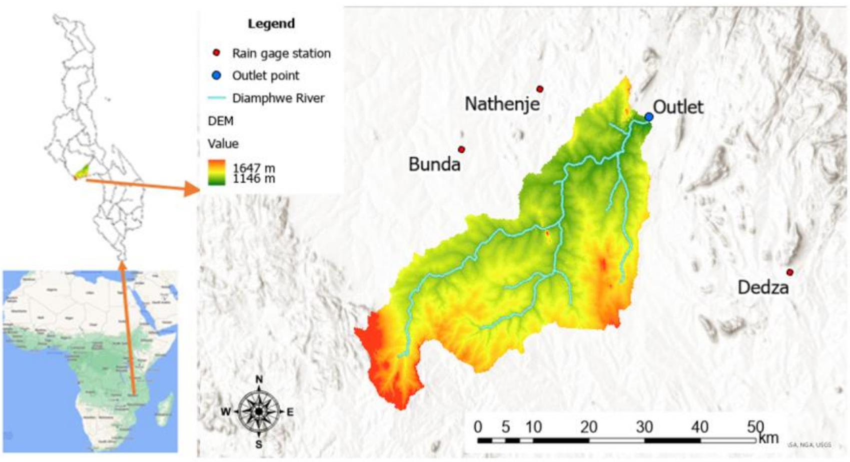


Fig. 1 The Diamphwe River basin in Malawi

Nearly 57.5% of the basin area is utilized for crop cultivation, and only 0.4% is utilized for natural and artificial forests (Malawi Government, 2016). The catchment area comprises flat dambos and plateaus which are rich in clay that retains water and is primarily used for forestry, livestock grazing/ranching, and winter vegetable cropping (Malawi Government, 2016; Mloza-Banda et al., 2001). The Köppen climate classification indicates that Malawi has a temperate climate with cold, dry winters and hot summers. (Belda et al., 2014). The Dedza and Dzalanyama forests, situated at higher elevations, receive more rainfall during the rainy season and, hence, experience a warm tropical climate with annual temperatures ranging from 3.5°C to 39°C. Malawi has three seasons including a warm and rainy season (November to April), a cool and dry season (May to August), and a hot and dry season (September to October). Over 95% of rainfall occurs during the rainy season. The Diamphwe River basin, however, experiences two seasons: the rainy season (November to April) and the dry season (May to October) (Malawi Government, 2016; Munthali et al., 2022). Over 90 percent of the households in the basin are farmers reliant on rain-fed agriculture (Malawi Government, 2019).

Rainfall and River Discharge Data

The daily rainfall data for 36 years, 1975-2010, was obtained from Malawi's Department of Climate Change and Meteorological Services. This Service monitors three weather stations: Dedza, Bunda, and Nathenje. Daily river discharge data for the same period was obtained from the Surface Water Division of the Department of Water Resources.

Statistical Methods and Analysis: Mann-Kendall Trend Test

The Mann-Kendall (MK) trend test is a non-parametric method for analyzing a time series of non-normally distributed data and censored monotonic environmental and climate data trends (Zuzani et al., 2019). The World Meteorological Organisation (WMO) recommends using the MK trend test to identify significant trends (Mann, 1945). MK is preferred due to its robustness against outliers and influential data gaps. MK only considers the sign of the slope, not its magnitude, when calculating the line formed by plotting the variable against time. The MK statistic (*S*) adds up the characters of the slopes to determine the presence of trends.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(X_j - X_k) \tag{1}$$

Where *S* is approximately normally distributed, provided the Z-transformation is employed, X_j *and* X_k are the data values at time *j* and *k,* respectively; *n* is the data length.

$$Z = \frac{S-1}{\sigma}\ if\ S > 0;\ \ Z = 0\ if\ S = 0;\ and\ Z = \frac{S+1}{\sigma}\ if\ S < 0 \tag{2}$$

Where σ is the data variance, *S* is related to Kendall's.

$$\tau = \frac{S}{D} \text{ where } D = \left[\frac{1}{2}n(n-1) - \frac{1}{2}\sum_{j=1}^{p} t_j(t_j - 1)\right]^{\frac{1}{2}} \left[\frac{1}{2}n(n-1)\right]^{\frac{1}{2}} \tag{3}$$

Where τ is the correlation coefficient, *D* is the difference in the data points.

The MK trend test identifies trends by comparing each data point to subsequent data points, and the final *S* value determines any trends. A positive value of *S* indicates an increasing trend, and a negative *S* value indicates a decreasing trend (Eq. 1). The *Z* involving *S*, establishes statistical significance (Eq.2). The study's MK analysis was performed using R and XLSTAT.

Pettitt Test as an Abrupt Jump (Change Point) Analysis

In a short-term and extended monotonic trend analysis, hydro-climatic data shows both gradual and abrupt, i.e., step-point, changes (Croitoru and Minea, 2015). Pettitt test detects change points to reveal transitions and abrupt changes in stream flow and rainfall (Pettitt, 1979). The test can identify a significant shift in a time series trend, even when the change's precise timing is uncertain.

RESULTS AND DISCUSSION

Figure 2 shows the average monthly rainfall and river discharge from 1975 to 2010. The monthly river discharge data shown in Figure 2 and Table 1 are the averages of the daily mean river flow data for each month from 1975 to 2010. Monthly rainfall represents the average total rainfall for each month from 1975 to 2010 at the three sites where rainfall was observed (Dedza, Bunda, and Nathenje).

These data show that rainfall and river discharge occur and vary in similar patterns. The rainy season, from November to April, demonstrates overall rainfall, and the highest rainfall month occurs in January (234.44 mm). River discharge was noted to change in tandem with rainfall, with the largest monthly average discharge occurring in February (25 m^3/s). The one-month lag between peak rainfall and peak river discharge is explained by the watershed effect and its temporary storage of water within a watershed.

To determine the variation of rainfall and river discharge for each month, the coefficient of variation (CV) was determined by dividing the standard deviation of each of the two parameters by their respective meaning (Table 1). The CV of rainfall was minimal during the rainy season, ranging from 0.32 to 0.72 (November to April), whereas in the dry season, the CV was extensive, ranging from 1.00 to 2.36. The CV for river discharge was highest in November, December, and April, with values of 2.35, 1.44, and 1.12, respectively. This indicates that monthly rainfall during the rainy season is stable, while rainfall during the dry season is small but highly variable. The river discharge fluctuations are extremely large in November and December at the start of the rainy season. The minimum and maximum river discharge during these months varies significantly from year to year, which should be considered when planning irrigation projects.

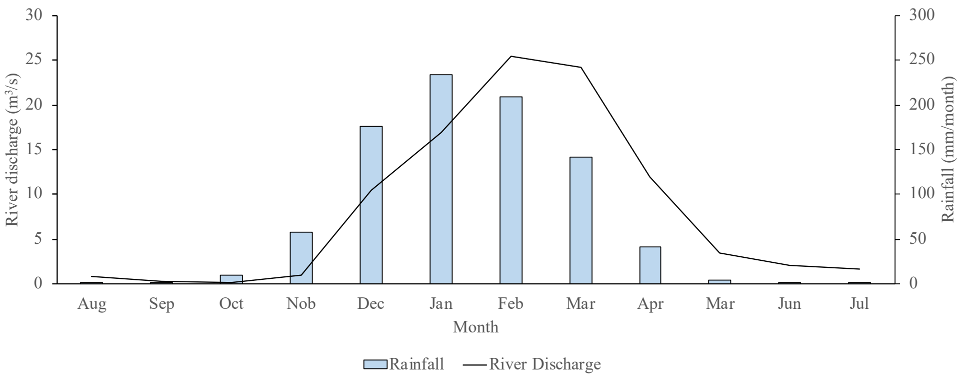


Fig. 2 Monthly averages for rainfall and river discharge for 36 years

Table 1 Rainfall and river discharge - monthly descriptive statistics

	Monthly average		Standard deviation		Coefficient of variation (CV)	
Month	Rainfall (mm/month)	River discharge (m^3/s)	Rainfall (mm/month)	River discharge (m^3/s)	Rainfall (-)	River discharge (-)
August	0.5	0.8	0.9	0.9	1.8	1.1
September	2.1	0.4	4.9	0.3	2.4	0.8
October	10.7	0.2	10.7	0.4	1.0	1.5
November	58.7	1.1	42.0	2.5	0.7	2.4
December	176.3	10.5	75.0	15.1	0.4	1.4
January	234.4	17.0	75.9	11.8	0.3	0.7
February	208.6	25.4	94.0	15.7	0.5	0.6
March	141.7	24.2	68.7	19.0	0.5	0.8
April	41.4	12.0	26.8	13.4	0.6	1.1
May	4.9	3.5	11.3	2.6	2.3	0.8
June	0.7	2.1	1.3	2.6	1.8	1.2
July	0.8	1.6	1.1	2.3	1.3	1.4

To understand the long-term trends over 36 years, average rainfall and river discharge in the rainy and dry seasons were analyzed, with results shown in Figure 3 and Table 2. Long-term trends of rainfall and river discharge were analyzed by the Mann-Kendall (MK) trend test (Table 2), whereby results show that the rainfall Z-value (magnitude of rainfall below or above its mean relative to its standard deviation) for the dry season, -1.799, a significant decreasing trend (indicated by asterisks). River discharge showed -2.073 (rainy season) and -1.889 (annual) significant decreasing trend in the 36-year project period.

The Pettitt test was conducted to detect change points in the trends. The Pettitt test results show that both rainfall and river discharge experienced a drastic trend drop in 2005 and 1988 respectively (Fig. 4). This indicates that river discharge transitioned in 1988, thereby progressing to the 1990s with considerably lower parameter values in the 36-year project period. This is consistent with the worst 1991-2000 El Nino period, which decreased 1992 agricultural production by 50% due to a 50% reduction in rainfall (Ngongondo, 2005). The significant decreasing trend in the two hydrologic parameters in Table 2 (rainfall and river discharge) and also their significant change point trend in 1988, are indicators of climate change in the basin, according to (Kayitesi et al., 2022; Klavins et al., 2014; Langat et al., 2017; Pervez and Henebry, 2015; Queen et al., 2023; Xu et al., 2004).

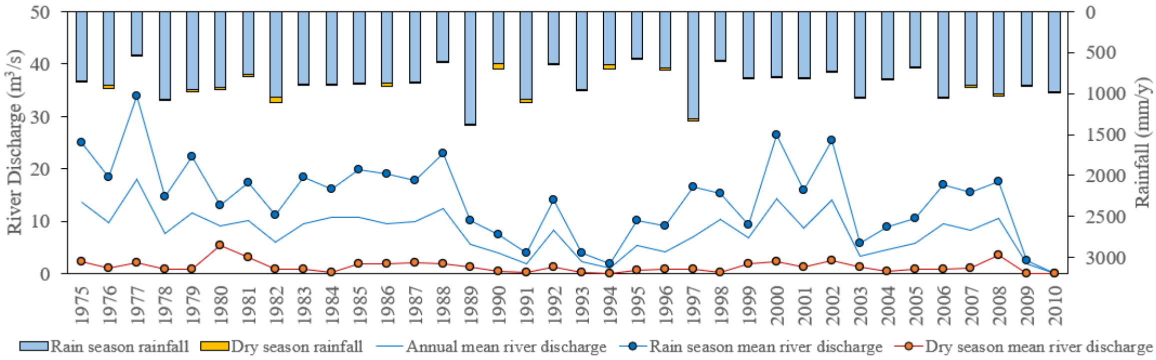
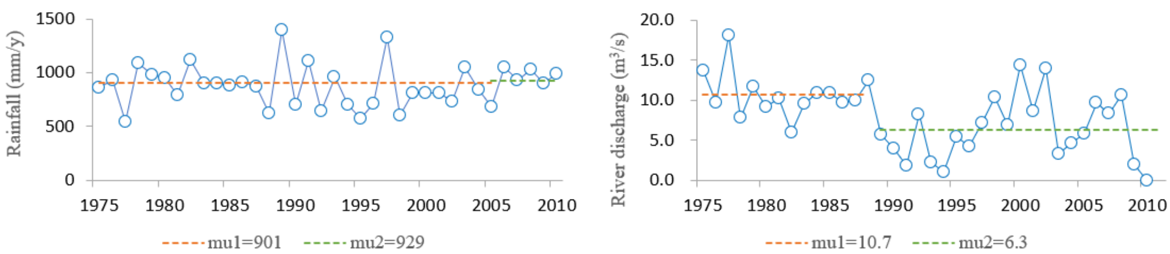


Fig. 3 Rainfall and river discharge descriptions

Table 2 Annual and Seasonal MK Trends

Rainfall	Mann-Kendall test			Pettitt test	
Period	Kendall tau	S-value	Z-value	k-value	t-value
Rainy season	0.003	2	0.01	81	2005
Dry season	-0.212	-133	-1.80*	156*	1991
Annual	-0.003	-2	-0.01	77	2005
River discharge	**Mann-Kendall test**			**Pettitt test**	
Period	Kendall tau	S-value	Z-value	k-value	t-value
Rainy season	-0.247	-147	-2.07**	194***	1988
Dry season	-0.146	-87	-1.22	122	1989
Annual	-0.225	-134	-1.89*	185**	1988

*Note: MK/Pettitt: *trend sig at 0.1 level, **trend sig. at 0.05 level; ***trend sig. at 0.01 level*



Note: mu1 is the mean value before the change and mu2 is the mean value after the change.

a) annual rainfall **b) river discharge**

Fig. 4 Pettitt tests for Diamphwe basin

Figure 5 shows the monthly average river discharge and rainfall for each year of the 36-year project period. To identify the trend within each month's cycle in the 36 years, the MK trend test was conducted for each month`s aggregated monthly average rainfall and river discharge (Table 3). The results indicate that only river discharge decreased significantly (negative Z-values) during the rainy season (November to April). During the dry season, within a month the rainfall trend decreased (negative Z-values) significantly in May and October and River discharge decreased in September. The results indicate that despite the seasonal cycles each year (6 months of rain season and 6 months of dry season), rainfall and river discharge trends also vary differently within each month.

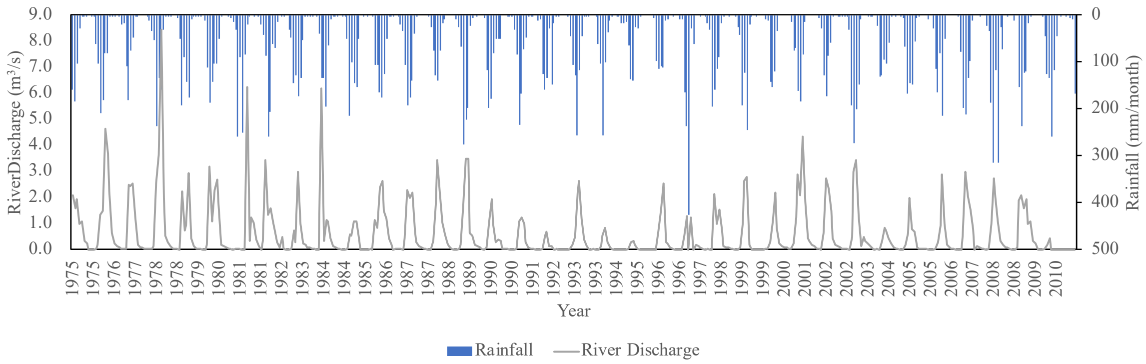


Fig. 5 Monthly averages for year-cycles

Table 3 Monthly MK trend analysis

Month	Period	Monthly Average Rainfall				Monthly Average River Discharge			
		Kendall tau	S	Z	p-value	Kendall tau	S	Z	p-value
November		-0.06	-36	-0.48	0.63	-0.14	-83	-1.17	0.24
December		0.04	26	0.34	0.73	-0.12	-74	-1.04	0.30
January	Rain Season	0.15	93	1.25	0.21	0.10	57	0.80	0.43
February		-0.11	-68	-0.91	0.36	-0.18	-109	-1.53	0.13
March		-0.02	-12	-0.15	0.88	-0.07	-41	-0.57	0.57
April		-0.17	-106	-1.43	0.15	-0.22	-132	-1.86*	0.06
May		-0.32	-195	-2.67***	0.01	-0.09	-54	-0.75	0.45
June		-0.28	-134	-2.12	0.03	0.01	8	0.10	0.92
July	Dry Season	-0.15	-83	-1.17	0.24	-0.03	-18	-0.24	0.81
August		-0.04	-17	-0.28	0.78	-0.12	-73	-1.02	0.31
September		-0.11	-54	-0.81	0.42	-0.22	-132	-1.86*	0.06
October		-0.21	-133	-1.80*	0.07	-0.15	-88	-1.24	0.22

*Note: MK/Pettitt: *trend sig at 0.1 level, **trend sig. at 0.05 level; ***trend sig. at 0.01 level*

CONCLUSION

This study demonstrated the long-term rainfall and river discharge trends in the Diamphwe River basin, Malawi, using data from 1975 to 2010. Rainfall and river discharge were found to be on a long-term declining trend. Within each month, the decreasing trends generally are observed in both rainy and dry seasons. It was also noted that 1988 was a transition year for the decreasing trend of the parameters in the basin. This coincided with the worst El Nino period of the century in the 1990s. “The decreasing trends in both rainfall and river discharge” are worrisome for farmers who rely on rainfed agriculture and for those who implement irrigation projects in the river basin. In addition, this study found that the river flow fluctuation was found to be large in November and December when the dry season changes to the rainy season, and in April when the rainy season changes to the dry season. These results may assist in the establishment of a regional water use plan for future agricultural production including the adoption of irrigation.

Future studies should examine changes in river flow in response to climate change using hydrologic models that simulate changes in river flow response to climate change, providing a more detailed picture of the potential situations and considering appropriate climate change strategies for the region.

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REFERENCES

Banda, L.C., Rivett, M.O., Kalin, R.M., Zavison, A.S.K., Phiri, P., Kelly, L., Chavula, G., Kapachika, C.C., Nkhata, M., Kamtukule, S., Mleta, P. and Nhlema, M. 2019. Water-isotope capacity building and demonstration in a developing world context, Isotopic baseline and conceptualization of a lake Malawi catchment. Water, 11 (12), 2600, Retrieved from DOI https://doi.org/10.3390/w11122600.

Barua, S., Muttil, N., Ng, A.W.M. and Perera, B.J.C. 2013. Rainfall trend and its implications for water resource management within the Yarra River catchment, Australia. Hydrological Processes, 27 (12), 1727-1738, Retrieved from DOI https://doi.org/10.1002/hyp.9311

Belda, M., Holtanová, E., Halenka, T. and Kalvová, J. 2014. Climate classification revisited, From Köppen to Trewartha. Climate Research, 59 (1), 1-13, Retrieved from DOI https://doi.org/10.3354/cr01204

Croitoru, A.E. and Minea, I. 2015. The impact of climate changes on rivers discharge in Eastern Romania. Theoretical and Applied Climatology, 120, 563-573, Retrieved from DOI https://doi.org/10.1007/s00704-014-1194-z

Food and Agriculture Organization of the United Nations (FAO). 2009. Global agriculture towards 2050. High Level Expert Forum, How to Feed The World in 2050, Food and Agricultural Organization, Rome, Italy, Retrieved from URL https://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global _Agriculture.pdf

Food and Agriculture Organization of the United Nations (FAO). 2013. Climate-smart agriculture sourcebook. Food and Agriculture Organization of the United Nations, Rome, Italy, Retrieved from URL https://www.fao.org/3/i3325e/i3325e.pdf

Gommes, R. 1996. Rainfall variability and drought in sub-Saharan Africa. Environment and Natural Resources Service (SDRN) and FAO Research, Extension and Training Division, Retrieved from URL https://open knowledge.fao.org/handle/20.500.14283/au042e

Kayitesi, N.M., Guzha, A. and C Mariethoz, G. 2022. Impacts of land use land cover change and climate change on river hydro-morphology, A review of research studies in tropical regions. Journal of Hydrology, 615, 128702, Retrieved from DOI https://doi.org/10.1016/j.jhydrol.2022.128702

Kelly, L., Bertram, D., Kalin, R., Ngongondo, C. and Sibande, H. 2020. A national scale assessment of temporal variations in groundwater discharge to rivers, Malawi. American Journal of Water Science and Engineering, 6 (1), 39-49, Retrieved from DOI https://doi.org/10.11648/j.ajwse.20200601.15

Klavins, M., Briede, A., Rodinov, V. and Kokorite, I. 2014. Long-term changes of the river runoff in Latvia. Boreal Environment Research, 7 (4), 447-456. Retrieved from URL https://www.researchgate.net/publication/255046289

Langat, P.K., Kumar, L. and Koech, R. 2017. Temporal variability and trends of rainfall and streamflow in Tana river basin, Kenya. Sustainability, 9 (11), 1963, Retrieved from DOI https://doi.org/10.3390/su9111963

Malawi Government. 2016. Diamphwe multipurpose dam and associated structures ESIA and RAP, Volume 1 main report. Environmental and Social Impact Assessment Draft Report, Ministry of Agriculture, Irrigation and Water Development, Malawi, Retrieved from URL https://documents1.worldbank.org/curated/en/192481468045236807/pdf/SFG1799-V1-EA-P153205-PUBLIC-Disclosed-2-11-2016.pdf

Malawi Government. 2019. Integrated household survey, National statistic office, Malawi. Retrieved from https://microdata-catalog.afdb.org/index.php/catalog/127/download/1044

Mann, H.B. 1945. Nonparametric tests against trends. Econometrica, 13 (3), 245, Retrieved from DOI https://doi.org/10.2307/1907187

Mloza-Banda, H.R., Banda, J.W., Lunduka, R. and Mohamoud, M.Y. 2001. The Dambo ecosystem of the Diamphwe and Lilongwe river catchments in central Malawi, I, Appraisal of resources availability and use. UNISWA Research Journal of Agriculture, Science and Technology, 5 (1). Retrieved from DOI https://doi.org/10.4314/uniswa-rjast.v5i1.4668

Muhammad Zaharaddeen, D., Shimizu, K., Yamazaki, Y., Mansouri, A. and Ousstous, L. 2023. Impact of a drip irrigation system on planning and management of water delivery in a large-scale irrigation scheme in

Morocco. International Journal Environmental and Rural Development, 14 (1), 38-44, Retrieved from https://doi.org/10.32115/ijerd.14.1_38

Munthali, G., Gumindoga, W., Chidya, R.C.G., Malota, M. and Muhoyi, H. 2022. Spatial and temporal variation in rainfall and streamflow, Dzalanyama catchment, Malawi. Water Practice and Technology, 17 (5), 1035-1045, Retrieved from DOI https://doi.org/10.2166/wpt.2022.045

Ngongondo, C.S. 2005. An analysis of long term rainfall variability, trend, and water availability Mulunguzi river area, Zomba, Malawi. Malawi Journal of Science and Technology, 7, 34-44, Retrieved from URL https://www.ajol.info/index.php/mjst/article/view/106765

Pervez, M.S. and Henebry, G.M. 2015. Assessing the impacts of climate and land use and land cover change on the freshwater availability in the Brahmaputra river basin. Journal of Hydrology, Regional Studies, 3, 285-311, Retrieved from DOI https://doi.org/10.1016/j.ejrh.2014.09.003

Pettitt, A.N. 1979. A non-parametric approach to the change-point problem. Journal of the Royal Statistical Society, Series C (Applied Statistics), 28 (2), 126-135., Retrieved from DOI https://doi.org/10.2307/2346729

Queen, L.E., Dean, S., Stone, D., Henderson, R. and Renwick, J. 2023. Spatiotemporal trends in near-natural New Zealand river flow. Journal of Hydrometeorology, 241-255, Retrieved from DOI https://doi.org/10.1175/JHM-D-22-0037.1

Saiyakit, D. and Boonthai Iwai, C. 2022. Effects of vermicompost and mineral water on the growth parameters of the KDML 105 rice cultivar. International Journal Environmental and Rural Development, 13 (2), 44-48, Retrieved from DOI https://doi.org/10.32115/ijerd.13.2_44

Sayemuzzaman, M. and Jha, M.K. 2014. Seasonal and annual precipitation time series trend analysis in north Carolina, United States. Atmospheric Research, 137, 183-194, Retrieved from DOI https://doi.org/10.1016/j.atmosres.2013.10.012

Spellman, F.R. and Drinan, J.E. 2001. Stream ecology and self-purification. Second Edition, CRC Press, Boca Raton, USA, ISBN 9781587160868.

Xu, Z.X., Chen, Y.N. and Li, J.Y. 2004. Impact of climate change on water resources in the Tarim river basin. Water Resources Management, 18, 439-458, Retrieved from DOI https://doi.org/10.1023/B:WARM.0000049142.95583.98

Zuzani, P.N., Ngongondo, C.S., Mwale, F.D. and Willems, P. 2019. Examining trends of hydro-meteorological extremes in the Shire river basin in Malawi. Physics and Chemistry of the Earth, 112, 91-102, Retrieved from DOI https://doi.org/10.1016/j.pce.2019.02.007