INVESTIGATION OF SYSTEM DESIGN CRITERIA AND THE CAPITAL COST OF VARYING DESIGN RETURN PERIODS FOR SOIL AND WATER CONSERVATION STRUCTURES

D. Otim, J. C. Smithers, A. Senzanje, R. van Antwerpen

HIGHLIGHTS

- Very few sediment yield events contribute to annual sediment yield.
- Any rainfall, runoff, and peak discharge event has the potential to generate the most extreme sediment yield event.
- Twenty year return period recommended for design of conservation structures.

ABSTRACT. *Design of conservation structures includes both hydrologic and hydraulic designs. Hydrologic design involves estimation of design floods which are required for the sizing of the hydraulic structures. The minimum recommended return period for the design of conservation structures is 10 years but due to the projected levels of risk, and the fact that a few large events are likely to be responsible for the majority of the erosion, the 10-year return period currently recommended may be inadequate. This study investigated system design criteria and the capital cost of varying design return periods for soil and water conservation structures in the sugar industry of South Africa. Observed rainfall data and results of runoff, peak discharge and sediment yield simulated using the Agricultural Catchments Research Unit (ACRU) model were utilized in this study. Relationships between extreme events of sediment yield and the rainfall, runoff and peak discharge events associated with them were analyzed and the capital cost of varying design return periods was also investigated. The results showed that only 0.2% of sediment yield events contributed up to 95% of the annual sediment yield simulated in the sugar production areas in South Africa and that any event of rainfall, runoff and peak discharge had the potential to generate an extreme sediment yield event provided the soil surface was not adequately protected. Based on a sustainable soil loss of 5 t ha^{-1}, the 20-year return period was recommended for the design of soil and water conservation structures. Furthermore, the capital cost implication of varying design return periods from the minimum 10-year return period ranged from an increase of 16% to 35% across the sugar industry. Therefore, given that soil erosion is associated with adverse effects on sustainable crop production and also increases in costs of replanting destroyed crops, the 20-year return period is recommended for the design of soil and water conservation structures in the sugar industry in South Africa.*

Keywords. *Capital cost, Design criteria, Erosion, Return period, Risk, Soil and water conservation.*

Waterways and contour banks are widely used structures in soil and water conservation and their designs entail both hydrologic and hydraulic designs (Morgan, 2005; Otim et al., 2019). However, it is recommended that soil management practices and agronomic measures are employed together with soil and water conservation structures for proper control of runoff and soil erosion from cultivated lands (Morgan, 2005; Sustainet, 2010; Krois and Schulte, 2014; Reinders et al., 2016). The aim of soil and water conservation is to ensure that the rate of soil formation is not exceeded by the rate of soil loss (Morgan, 2005) and, in the sugar industry of South Africa, sustainable soil losses are in the range 5 to 10 t ha^{-1}.year^{-1} (Matthee and Van Schalkwyk, 1984; Le Roux et al., 2008). However, most of the erosion occurs in relatively few events and consideration should be given to individual rainfall events which initiate key hydrological responses such as stormflow and sediment yield (Schulze et al., 2011).

Hydrologic design encompasses design flood estimation which is required for the sizing of hydraulic structures,

Submitted for review in September 2019 as manuscript number NRES 13714; approved for publication as a Research Article by the Natural Resources & Environmental Systems Community of ASABE in May 2020.

The authors are **Daniel Otim,** Student, Agricultural Engineering, School of Engineering, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa, and Lecturer, Department of Agricultural Mechanisation and Irrigation Engineering, Busitema University, Tororo, Uganda; **Jeffrey C Smithers,** Professor, Agricultural Engineering, School of Engineering, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa, and National Centre for Engineering in Agriculture, University of Southern Queensland, Toowoomba, Australia; **Aidan Senzanje,** Senior Lecturer, Agricultural Engineering, School of Engineering, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa; and **Rianto van Antwerpen,** Professor, South African Sugarcane Research Institute, Mount Edgecombe, South Africa, and Department of Soil, Crops and Climate Sciences, University of the Free State, Bloemfontein, South Africa. **Corresponding author:** Daniel Otim; University of KwaZulu-Natal College of Agriculture Engineering and Science - Agricultural Engineering, Private Bag X01, Scottsville Pietermaritzburg Pietermaritzburg 3209, South Africa; phone: +27717114399; e-mail: danotim@gmail.com.

Table 6. Hydraulic sections and design implementation costs of soil and water conservation structures in the four homogenous climatic zones in the sugar industry of South Africa.

Region	Return Period (year)	Design Discharge ($m^3 s^{-1}$)	Bottom Slope (%)	Hydraulic Mean Depth (m)	Top Width (m)	Area (m^2)	Hydraulic Radius (m)	Flow Velocity ($m s^{-1}$)	Cost (R)	Cost Increase (%)
North Coast	10	1.2	0.5	0.75	5.50	2.8	0.48	0.50	6116	0
	20	1.9	0.5	0.80	6.00	3.2	0.51	0.60	7117	16
South Coast	10	1.6	0.5	0.80	5.50	2.9	0.50	0.57	6524	0
	20	2.7	0.5	0.90	6.50	3.9	0.57	0.74	8674	33
Zululand and Irrigated	10	1.5	0.5	0.80	5.00	2.7	0.50	0.57	5931	0
	20	2.5	0.5	0.90	6.00	3.6	0.57	0.74	8006	35
Midlands	10	1.1	0.5	0.75	5.00	2.5	0.47	0.47	5560	0
	20	1.7	0.5	0.80	6.00	3.2	0.51	0.58	7117	28

ACKNOWLEDGEMENTS

We are highly indebted to the South African Sugarcane Research Institute (SASRI) for funding this research and Dr Peter Tweddle for the guidance in costing the construction of soil and water conservation structures.

REFERENCES

Aduah, M. S., Jewitt, G. P., & Warburton Toucher, M. L. (2017). Assessing suitability of the ACRU hydrological model in a rainforest catchment in Ghana, West Africa. *Water Sci., 31*(2), 198-214. https://doi.org/10.1016/j.wsj.2017.06.001

ASABE Standards (2012). S268.5: Design, layout, construction, and maintenance of terrace systems. St. Joseph, MI: ASABE.

Barbier, E. B. (1990). The farm-level economics of soil conservation: The uplands of Java. *Land Econ., 66*(2), 199-211. https://doi.org/10.2307/3146369

Botha, F., Buchanan, G. F., Mann, Q. V., McArthur, D., Meyer, J. H., Schumann, A. W.,... Wood, R. A. (1999). ldentification and management of the soils of the South African sugar industry. Mount Edgecombe, RSA: SASEX.

Carey, B. W., Stone, B., Norman, P. L., & Shilton, P. (2015). Contour banks. In S. Butcher, C. Campbell, D. Green, F. Hamilton, L. Skopp, & M. Willson (Eds.), Soil conservation guidelines for Queensland (pp. 1-34). Brisbane, Australia: Department of Science, Information Technology and Innovation.

Gebremedhin, B., & Swinton, S. M. (2003). Investment in soil conservation in northern Ethiopia: The role of land tenure security and public programs. *Agric. Econ., 29*(1), 69-84. https://doi.org/10.1111/j.1574-0862.2003.tb00148.x

Hui-Ming, S., & Yang, C. T. (2009). Estimating overland flow erosion capacity using unit stream power. *Int. J. Sediment Res., 24*(1), 46-62. https://doi.org/10.1016/S1001-6279(09)60015-9

Kienzle, S. W., & Schmidt, J. (2008). Hydrological impacts of irrigated agriculture in the Manuherikia catchment, Otago, New Zealand. J. Hydrol. (NZ), 67-84.

Krois, J., & Schulte, A. (2014). GIS-based multi-criteria evaluation to identify potential sites for soil and water conservation techniques in the Ronquillo watershed, northern Peru. *Appl. Geogr., 51*, 131-142. https://doi.org/10.1016/j.apgeog.2014.04.006

Le Roux, J. J., Morgenthal, T. L., Malherbe, J., Pretorius, D. J., & Sumner, P. D. (2008). Water erosion prediction at a national scale for South Africa. *Water SA, 34*(3), 305-314. https://doi.org/10.4314/wsa.v34i3.180623

Lorentz, S. A., Kollongei, J., Snyman, N., Berry, S. R., Jackson, W., Ngaleka, K.,... le Roux, J. (2012). Modelling nutrient and sediment dynamics at the catchment scale. WRC Report No. 1516/3/12. Pretoria, RSA: Water Research Commission. Retrieved from http://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/1516-3-121.pdf

MacVicar, C. N., De Villiers, J. M., Loxton, R. F., Verster, E., Lambrechts, J. J. N., Merryweather, F. R.,... Harmse, H. J. V. M. (1977). Soil classification. A binomial system for South Africa. Pretoria, RSA: Department of Agricutural Development.

Matthee, J. F. I. G., & Van Schalkwyk, C. J. (1984). A primer on soil conservation (Vol. 339). Pretoria, RSA: Department of Agriculture.

McAlister, E. M. F., & Russel, W. B. (1998). Construction and maintenace of contour banks. In M. A. Abbott (Ed.), Conservation of farmland in KwaZulu-Natal (pp. 60-71). Pietermaritzburg, RSA: KwaZulu-Natal Department of Agriculture.

Mkhabela, T. S. (2002). Farm size and soil loss: Prospects for a sustainable agriculture in KwaZulu-Natal. *Agrekon, 41*(2), 134-145. https://doi.org/10.1080/03031853.2002.9523584

Morgan, R. P. C. (2005). *Soil erosion and conservation*. Blackwell Publ.

Mthembu, I., Lyne, P., Bezuidenhout, C., Collings, K., de Haas, O., Wilkinson, D.,... Maher, G. W. (2011). Mapping land suitability for mechanized harvesting in cane growing areas, South Africa. Report No. 07RE06. Mount Edgecombe: South African Sugarcane Research Institute.

Nemeth, M. W., Kienzle, S. W., & Byrne, J. M. (2012). Multi-variable verification of hydrological processes in the upper North Saskatchewan River basin, Alberta, Canada. *Hydrol. Sci. J., 57*(1), 84-102. https://doi.org/10.1080/02626667.2011.633917

Otim, D. (2020). Development of updated design norms for soil and water conservation structures in the sugar industry of South Africa. PhD diss. Pietermaritzburg, RSA: University of KwaZulu-Natal, School of Engineering.

Otim, D., Smithers, J. C., Senzanje, A., & Van Antwerpen, R. (2019). Design norms for soil and water conservation structures in the sugar industry of South Africa. *Water SA, 45*(1), 29-40. https://doi.org/10.4314/wsa.v45i1.04

Otim, D., Smithers, J., Senzanje, A., & van Antwerpen, R. (2020). Verification of runoff volume, peak discharge and sediment yield simulated using the ACRU model for bare fallow and sugarcane fields. *Water SA, 46*(2 April).

Palmer, T., & Ainslie, A. (2006). Country pasture/forage resource profiles-South Africa. Rome, Italy: United Nations FAO.

Reij, C., Scoones, I., & Toulmin, C. (2013). Sustaining the soil: Indigenous soil and water conservation in Africa. Oxford, U.K.: Routledge. https://doi.org/10.4324/9781315070858

Reinders, F. B., Oosthuizen, H., Senzanje, A., Smithers, J. C., van der Merwe, R. J., van der Stoep, I., & van Rensburg, L. (2016). Development of technical and financial norms and standards for drainage of irrigated lands. Report No. TT 655/15. 3. Pretoria, RSA: Water Research Commission. Retrieved from http://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/2026%20-2-15.pdf

Rootzen, H., & Katz, R. W. (2013). Design life level: Quantifying risk in a changing climate. *Water Resour. Res., 49*(9), 5964-5972. https://doi.org/10.1002/wrcr.20425

Russell, W. B. (1998). The cost of farmland degradation. In M. A. Abbott (Ed.), Conservation of farmland in KwaZulu-Natal (pp. 30-34). Pietermaritzburg, RSA: KwaZulu-Natal Department of Agriculture.

SASA. (2002). Standards and guidelines for conservation and environmental management in the South African sugar industry. Mount Edgecombe, RSA: South African Sugar Association.

SASA. (2016). South African sugar industry directory 2016/2017. Mount Edgecombe, RSA: SASA.

SASA. (2018). Where to find us. SASRI. Retrieved from http://www.sasa.org.za/Libraries/Maps/Map_of_Operational_Areas.sflb.ashx

SASRI. (2019a). Costing machinery systems. Mechanisation Report No. 1. Mount Edgecombe, RSA: South African Sugarcane Research Institute. Retrieved from https://sasri.org.za/mechanisation/

SASRI. (2019b). Systems and costs of land preparation, planting and ratoon management. Mechanisation Report No. 2. Mount Edgecombe, RSA: Sugarcane Research Institute. Retrieved from https://sasri.org.za/mechanisation/

Schulze, R. E. (1975). Catchment evapotranspiration in the Natal Drakensberg. PhD diss. Pietermaritzburg, RSA: University of Natal, Department of Geography.

Schulze, R. E. (1995). Hydrology and agrohydrology: A text to accompany the ACRU 3.00 agrohydrological modelling system. WRC Report TT69/95. Pretoria, RSA: Centre for Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg Campus.

Schulze, R. E. (2013). Modelling impacts of land use on hydrological responses in South Africa with the ACRU model by sub-delineation of quinary catchments into land use dependent hydrological response units. Pietermaritzburg, RSA: Centre for Water Resources Research, University of KwaZulu-Natal.

Schulze, R. E., & Smithers, J. C. (2004). The ACRU agrohydrological modelling system as of 2002: Background, concepts, structure, output, typical applications and operations. WRC Report 749/1/04. Pretoria, RSA: Centre for Water Resources Research, University of KwaZulu-Natal,.

Schulze, R. E., Hewitson, B. C., Barichievy, K. R., Tadross, M. A., Kunz, R. P., Horan, M. J., & Lumsden, T. G. (2011). Methodological approaches to assessing eco-hydrological responses to climate change In South Africa. WRC Report No. 1562/1/10. 197. Pretoria, RSA: Water Research Commission. Retrieved from http://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/1562-1-10%20Hydroclimatology1.pdf

Schulze, R. E., Schmidt, E. J., & Smithers, J. C. (2004). Visual SCS - SA user manual vers. 1.0: PC based SCS design flood estimates for small catchments in Southern Africa. ACRUcons Report No. 52. Pietermaritzburg, RSA: School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal. Retrieved from https://www.worldcat.org/title/scs-sa-user-manual-pc-based-scs-design-flood-estimates-for-small-catchments-in-southern-africa/oclc/704186936

Shaxson, T. F. (1985). Changing approaches to soil conservation. In T. F. Shaxson (Ed.), Proc. Int. Conf. on Soil Conserv. Soil Conservation Programme, Soil Resources Management and Conservation Service, Land and Water Development Division.

Smithers, J. C., Mathews, P., & Schulze, R. E. (1996). The simulation of runoff and sediment yield from catchments under sugarcane production at La Mercy, using the ACRU model. ACRUcons Report No. 13. Pietermaritzburg, RSA: Agricultural Engineering, School of Engineering, College of Agriculture, Engineering and Science, University of KwaZulu-Natal.

Smithers, J. C., Schulze, R. E., Lecler, N. L., Kienzle, S. W., Lorentz, S. A., & Kunz, R. P. (1995). User guidelines for setting up information. In J. C. Smithers, & R. E. Schulze (Eds.), ACRU Agrohydrological modelling system: User manual version 3.00 (pp. 1-190). Pietermaritzburg, RSA: Department of Agricultural Engineering, University of Natal.

Sulaeman, D., & Westhoff, T. (2020). The causes and effects of soil erosion, and how to prevent it. World Resources Institute Website. Retrieved from https://www.wri.org/blog/2020/01/causes-effects-how-to-prevent-soil-erosion

Sustainet, E. A. (2010). Technical manual for farmers and field extension service providers: Conservation agriculture. Nairobi, Kenya: Sustainable Agriculture Information Initiative.

USDA-NRCS. (2007). Threshold channel design. In USDA-NRCS (Ed.), Part 654 *Stream restoration design national engineering handbook* (pp. 1-43). Washington, DC: USDA-NRCS.

USDA-NRCS. (2011). Terraces. In USDA (Ed.), *Engineering field handbook.* Washington, DC: USDA-NRCS.

Williams, J. R. (1975). Sediment-yield prediction with universal equation using runoff energy factor. In J. R. Williams (Ed.), Present and prospective technol. for predicting sediment yield and sources (pp. 244-252). Washington, DC: ARS.

Williams, J. R., & Berndt, H. D. (1977). Sediment yield prediction based on watershed hydrology. *Trans. ASAE, 20*(6), 1100-1104. https://doi.org/10.13031/2013.35710

Young, A. (1989). *Agroforestry for soil conservation* (Vol. 4). Wallingford, U.K.: CAB Int.