Journal of African Earth Sciences 55 (2009) 205–213

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Recent glacial recession and its impact on alpine riverflow in the Rwenzori Mountains of Uganda

Richard G. Taylor [a,*], Lucinda Mileham [a], Callist Tindimugaya [b], Leo Mwebembezi [b]

[a] Department of Geography, University College London, Gower Street, London WC1E 6BT, UK
[b] Water Resources Management, Ministry of Water and Environment, P.O. Box 19, Entebbe, Uganda

ARTICLE INFO

Article history:
Received 6 January 2009
Received in revised form 29 March 2009
Accepted 9 April 2009
Available online 5 May 2009

Keywords:
Glacier
Tropics
Riverflow
Climate change
Africa

ABSTRACT

The limited number and duration of hydrological measurements in the East African Highlands inhibit current understanding of the impact of glacial recession on alpine riverflow. From historical records and surveys conducted in the dry season of 2005 and wet season of 2007, we report (1) recent changes in the terminal positions of large valley glaciers (Speke, Elena) and (2) spot measurements of alpine riverflow along altitudinal transects of the principal river (River Mubuku) draining alpine icefields in order to assess the relative contribution of icefields and underlying ecotones to river discharge. Observed acceleration in the rates of termini retreat of the Speke and Elena glaciers since the late 1960s is attributed, in part, to the convex–concave slope profile in which these valley glaciers reside. We show that current glacial recession has a negligible impact on alpine riverflow. Spot measurements of meltwater discharges indicate that icefields contribute considerably less than 2% of the river discharge at the base of the Rwenzori Mountains during both dry and wet seasons. An anomalously high specific discharge of the River Mubuku (1730 mm a^{-1}) arises from high rates of precipitation exceeding 2000 mm a^{-1} below alpine icefields within Heath-moss and Montane forest ecotones that occupy more than half of the river's gauged catchment area. For other tropical alpine icefields representing a tiny fraction (<1%) of alpine river catchment areas (e.g. Irian Jaya, Kilimanjaro, Mount Kenya), glacial meltwater discharges are similarly expected to contribute a negligible proportion of alpine riverflow.

1. Introduction

Tropical alpine glaciers form important reservoirs of fresh water that store seasonal inputs of precipitation, associated with the movement of the Inter-tropical Convergence Zone (ITCZ), and sustain meltwater discharges during drier periods. In the South American Andes, glaciers serve to regulate alpine riverflow upon which downstream communities rely for year-round water supplies (Bradley et al., 2006). Meltwater discharges from alpine icefields covering ~10% of the mesoscale Rio Santo basin of Peru are estimated to provide at least 12% of the annual river discharge (Mark and Seltzer, 2003) and ~40% of the dry-season river discharge (Mark et al., 2005). Glacial recession since the 19th century has led to increased seasonality and overall reductions in riverflow (Mark and Seltzer, 2003; Bradley et al., 2006).

In the East African Highlands, the observed reduction in areas covered by glaciers since the early 20th century (e.g. Hastenrath, 1984; Kaser and Noggler, 1996; Kaser and Osmaston, 2002; Taylor et al., 2006) has led to concerns over the impact of deglaciation on river discharge during the dry season (Gasse, 2002; Thompson et al., 2002) and the risk of flooding during the rainy season (Uganda Meteorology Department, 2006). Desanker (2002) asserts that several rivers on Kilimanjaro are drying out during the dry season "due to the loss of the frozen reservoir". In contrast, Temple (1968) and Kaser et al. (2004) contend that glacial meltwater discharges provide insignificant contributions to alpine riverflow in the Rwenzori Mountains and Kilimanjaro, respectively.

The limited number and duration of hydrological measurements in the East African Highlands inhibit current understanding of the impact of shrinking icefields on alpine riverflow. In the Rwenzori Mountains, no measurements of riverflow have previously been collected above its base with the exception of a few spot measurements of glacial meltwater discharges summarised by Temple (1968). We report spot measurements of riverflow in the Rwenzori Mountains along altitudinal transects of the principal river (River Mubuku) draining alpine icefields during both dry and wet seasons. We use this new dataset together with historical records to assess the relative contribution of icefields and underlying ecotones to river discharge. We also report on recent changes in the terminal positions of regularly monitored valley glaciers.

* Corresponding author. Tel.: +44 207 679 0591; fax: +44 207 679 0565.
E-mail address: r.taylor@geog.ucl.ac.uk (R.G. Taylor).

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doi:10.1016/j.jafrearsci.2009.04.008

2. Hydrology of the Rwenzori Mountains

The Rwenzori Mountains are situated within the western arm of the East African Rift System (Fig. 1a) and comprise an uplifted block (horst) of Precambrian crystalline rocks. Occupying an area of 3000 km^2, the horst is bounded to the north and south by grabens that contain Lakes Albert and Edward, respectively. The Rwenzori horst tilted up in an ESE to WNW direction (Fig. 2), 4 km above the surrounding peneplain in the Late Pliocene (Taylor and Howard, 1998). Alternating cycles of glacial and fluvial erosion, extensively reviewed by Osmaston (1989), produced deeply incised valleys. Catchment areas draining eastwards are considerably larger than those draining to the west due to the orientation of the horst's tilt. From moraine evidence, Osmaston (2006) estimates that glaciers covered ~260 km^2 between 10 and 20 ka before present (BP) (Last Glacial Maximum) and ~10 km^2 between 100 and 200 a BP (Little Ice Age).

The precise onset of modern glacial recession in the Rwenzori Mountains remains unclear. Several authors (Hastenrath, 2001; Mölg et al., 2003, 2006; Kaser et al., 2004) contend that deglaciation started around 1880 AD as a result of an abrupt reduction in precipitation inferred from a reconstruction of the levels of Lake Victoria over the 19th century (Nicholson and Yin, 2001). Recent palaeolimnological evidence (Russell et al., 2008) suggests that glacial recession started slightly earlier between 1860 and 1870 AD similar to other tropical alpine icefields. Field research carried out in the 1950s (Menzies, 1951; Bergstrøm, 1955; Whittow et al., 1963), early 1990s (Kaser and Noggler, 1991, 1996; Talks, 1993) and from 2003 to 2005 (Taylor et al., 2006) indicate that the area covered by alpine glaciers has reduced from 7.5 km^2 in 1906 to <1 km^2 in 2003.

Glaciers currently occur on three mountains: Stanley, Speke and Baker. Over the last century, glaciers and their meltwater flows formed headwaters of primarily three rivers in the Rwenzori

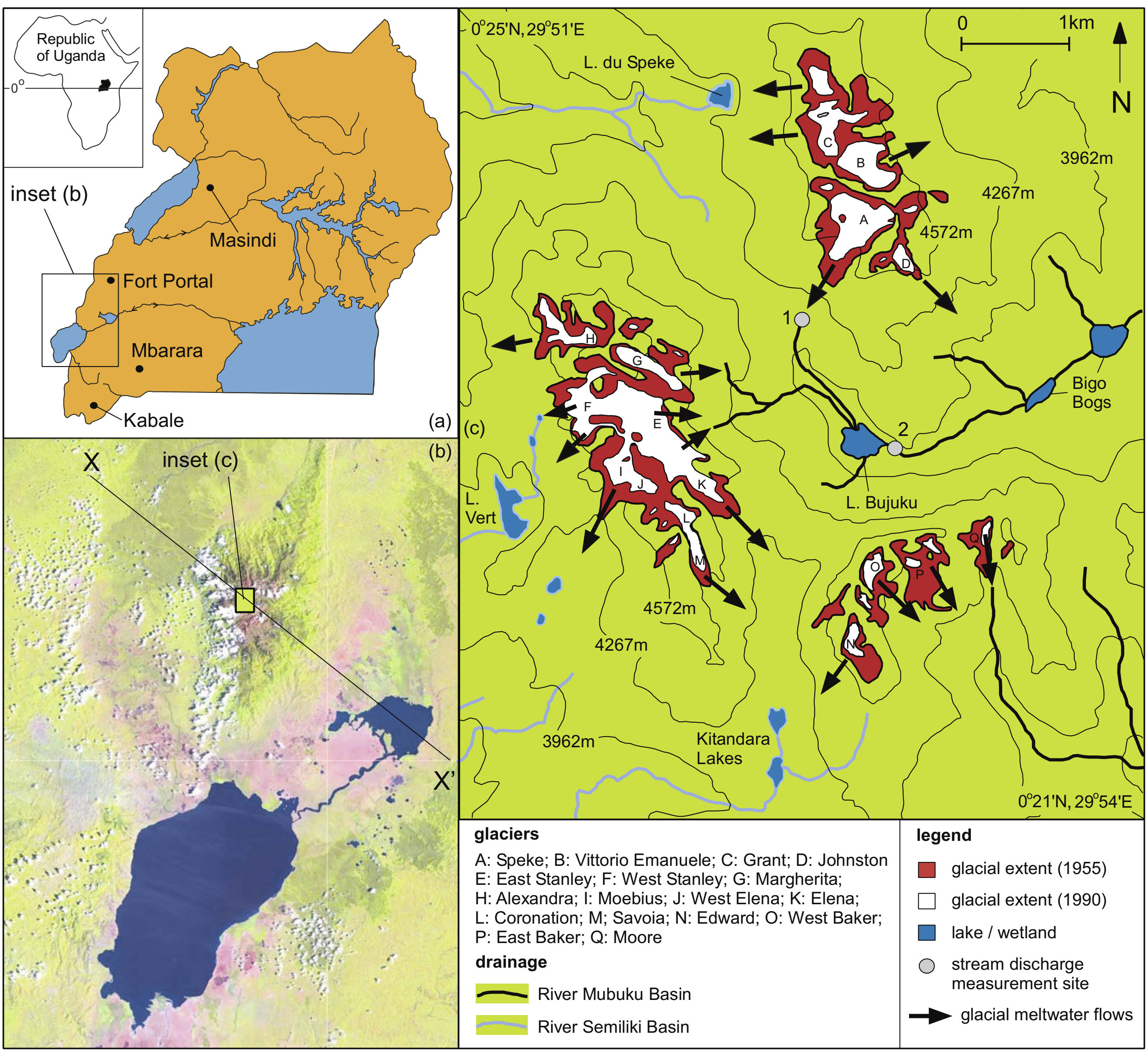

Fig. 1. (a) Map of Uganda showing the location of the Rwenzori Mountains in Uganda and regional meteorological stations; (b) LandSat7 satellite image showing the Rwenzori horst in relation to Lakes George and Edward as well as the orientation of the cross-section (*X*–*X'*) in Fig. 2; and (c) map of glacial extent and drainage in the Central Rwenzori Massif (redrawn and adapted from Osmaston and Kaser, 2001) showing the direction of meltwater discharges and location of river discharge monitoring stations.

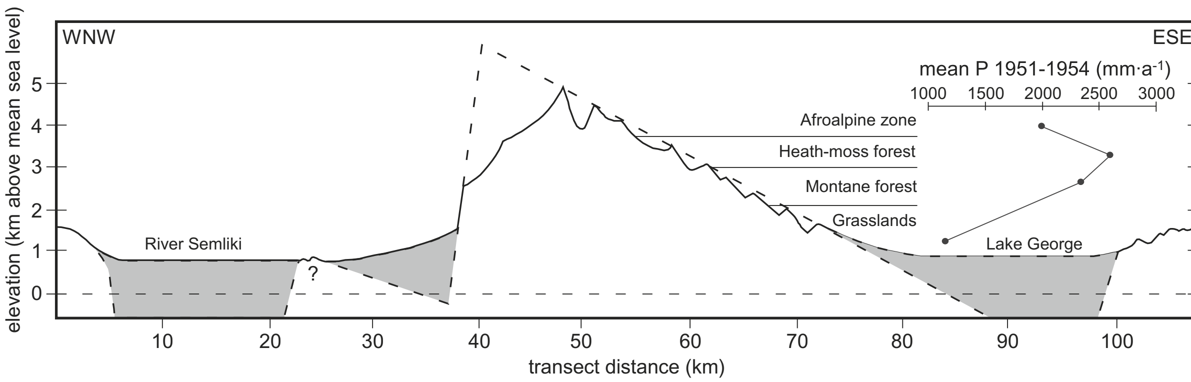

Fig. 2. A cross-sectional sketch of the Rwenzori horst tilting upwards from the ESE to WNW (adapted from Osmaston (1989)); vertical exaggeration is × 4. Alpine precipitation observed from 1951 to 1954 by Osmaston (2006) and the main vegetation zones (ecotones) are indicated.

Mountains: the River Mubuku that flows eastward in the Republic of Uganda and Rivers Butawu and Lusilube which drain westward in the Democratic Republic of Congo (Figs. 1c and 3). Of the remaining glaciers in the Central Rwenzori Massif (Fig. 1c), most of the largest including East Stanley (E), Speke (A), Vittorio Emanuele (B), and Margherita (G) glaciers form headwaters of the River Mubuku.

Precipitation in the Rwenzori Mountains is bimodal; wetter periods occur from March to May and August to November. Apart from the seasonal control on precipitation exerted by movement of the ITCZ, there is a strong orographic effect on local precipitation. Mean annual precipitation from 1964 to 1995 recorded at Kilembe (Fig. 3) at an elevation of 1370 m above mean sea level (mamsl) is 1540 mm a^{-1} whereas this flux drops to 890 mm a^{-1} just 11 km away but 410 m lower in elevation at Kasese Airport (960 mamsl). Osmaston (1989) collected the only sustained measurements of precipitation at four locations in the Rwenzori Mountains from 1951 to 1954 at higher elevations than Kilembe. These observations similarly show pronounced variations in mean annual precipitation with altitude from 1951 to 1954 (Fig. 2). From the base of the mountains around 1250 mamsl, precipitation was observed to increase with rising elevation from 1150 mm a^{-1} to a maximum annual precipitation of 2600 mm a^{-1} recorded at 3290 mamsl in the Heath-moss forest zone. Above this, precipitation decreased to 2000 mm a^{-1} at Lake Bujuku in the Afroalpine zone (3990 mamsl) within the Central Rwenzori Massif.

3. Methodology

Historical records of riverflow draining alpine areas of the Rwenzori Mountains were supplied by the Water Resources Management Department of Uganda. Spot measurements of riverflow in the River Mubuku were collected at six locations ranging in elevation from 2845 to 4104 mamsl (Figs. 1 and 3) during one dry season in 2005 (25 January–2 February) and one wet season in 2007 (20–24 April). Due to the highly turbulent nature of alpine stream reaches that commonly feature large boulders, dilution gauging (Day, 1976) was employed rather than the more common, velocity-area approach. We used the finite mass dilution method (Okunishi et al., 1992) wherein a known quantity of tracer is injected to a river and its concentration is monitored continuously downstream until the tracer's concentration returns to background. The dilution of the tracer is proportional to the discharge assuming that the mass of applied tracer is conserved between the point of injection and point of measurement downstream. Eq. (1) defines the conservation of mass for a time-varying concentration of tracer (c_t) monitored continuously after injection of a mass (M) into a river discharge (Q) until the measured concentration returns to the tracer's background concentration (c_b).

$$Q\int_0^\infty [c_t - c_b]\partial t = M \quad (1)$$

NaCl was used as a tracer since applied concentrations and durations of exposure would not be deleterious to the freshwater biota. Concentrations of aqueous NaCl can also be easily and reliably measured using an electrical conductivity (EC) meter. All EC measurements compensated for substantial changes in water temperature (3–22 °C) within the alpine environment and were recorded in terms of a standard temperature of 25 °C. Calibration of the EC meter was conducted daily against prepared standards (10, 20, 50 and 100 mg L^{-1}) in order to account for potential drift in meter readings. Background EC measurements of riverflow varied from 9 to 61 µS cm^{-1} depending upon season and river elevation. Pre-weighed, dry quantities of NaCl ranging from 0.25 to 0.50 kg were injected to the river inducing peak EC measurements that were typically 100–500% greater than background. EC was recorded every 10 s at a distance of 20–25 m downstream from injection (equivalent to 20–30 channel widths). All salt dilution gaugings were done in duplicate; calculated uncertainty in flow estimates was ⩽10%. Changes in the terminal positions of the two largest valley glaciers in the Rwenzori Mountains (Speke, Elena) were surveyed in relation to past field markers as well as those established by our surveys using a measuring tape and hand-held GPS (Etrex Summit).

4. Results and discussion

4.1. Retreat of Speke and Elena valley glaciers since 1990

Continued retreat of the terminal positions of the Speke and Elena glaciers is observed (Fig. 4) relative to positions reported in 1990 (Kaser and Noggler, 1991, 1996; Kaser and Osmaston, 2002). The Speke Glacier has retreated 380 m between 1990 and 2003 whereas the Elena Glacier has retreated 320 m between 1990 and 2007. For the more frequently monitored Speke Glacier, acceleration in the rate of termini retreat is evident from the late 1960s to present. The implication that the rate of glacier mass losses in the Rwenzori Mountains has recently increased is not, however, supported by changes in glacial area reported by Taylor et al. (2006). These data show that the rate of decline in glacial extent since 1990 is consistent with the overall trend of ∼−0.7 km^2 per decade since 1906. Rapid retreat in the terminus of the Speke Glacier followed prolonged thinning over the entire glacier (Kaser and Noggler, 1996) which, residing on a convex–concave slope profile, eventually resulted in the separation of the valley glacier's tongue from its area of accumulation (Fig. 5). A similar sequence of thinning followed by rapid terminal retreat (76 m a^{-1} from 2005 to 2007) has more recently been observed for the Elena Glacier.

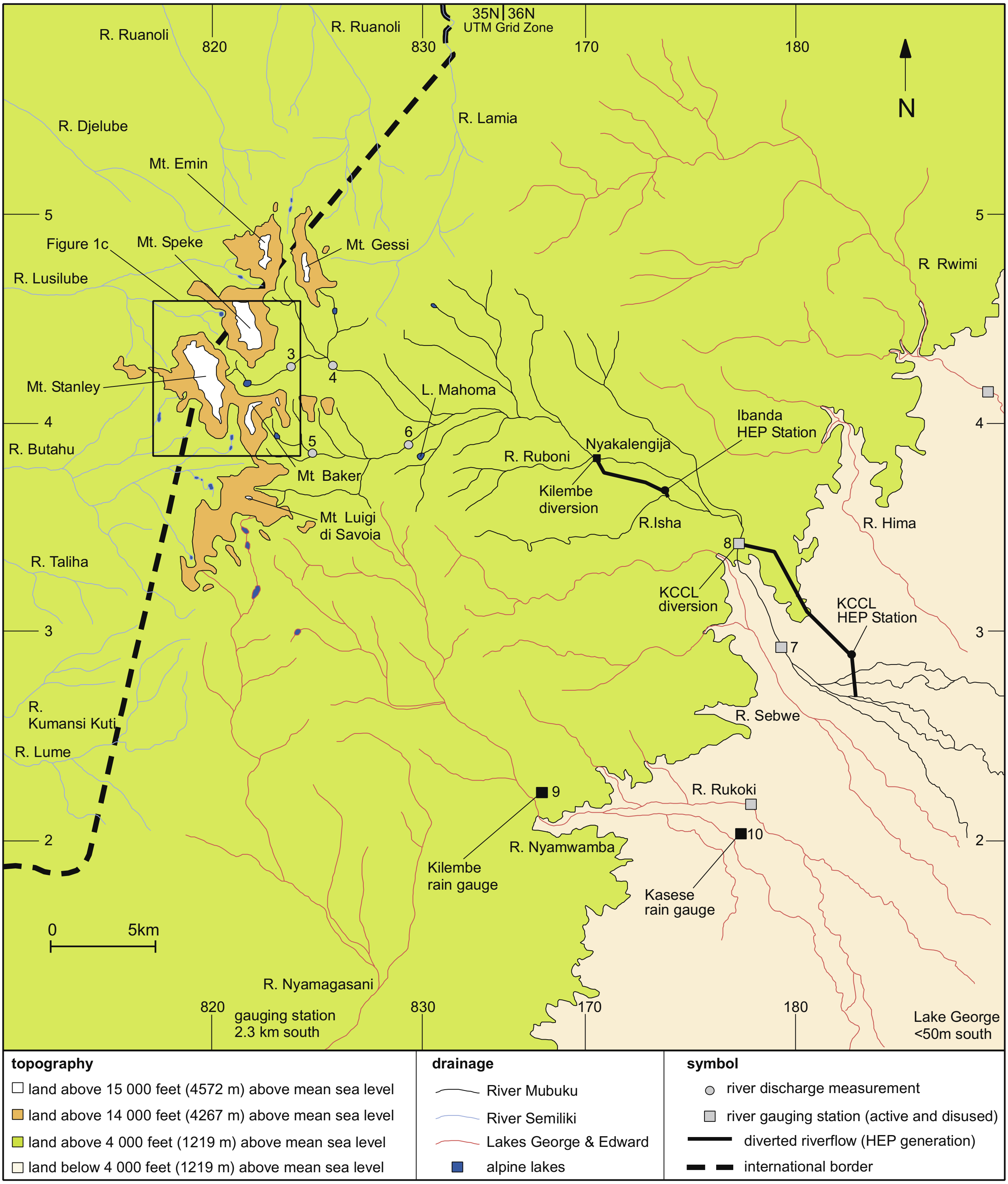

Fig. 3. Map of the drainage network for the Rwenzori Mountains. The international border divides the Republic of Uganda to the east and the Democratic Republic of Congo to the west. Redrawn from the Fort Portal (1:250,000) sheet, NA-36-I3 (Lands and Surveys Department Uganda, 1961).

4.2. Contributions of receding glaciers to alpine riverflow

Regular monitoring of riverflow at the base of the Rwenzori Mountains is currently restricted to the River Nyamagasani though historical records exist for Rivers Mubuku, Rwimi and Rukoki (Fig. 3). Inconsistencies and gaps identified in these records (Taylor and Aggrey, 2004) limit the analysis of historical data to Rivers Mubuku and Nyamagasani (Fig. 6). The old gauge for the River Mubuku (station 7 in Fig. 3) has a catchment area of 256 km^2 with a mean discharge from 1954 to 1965 of 14 m^3 s^{-1} (data gaps occur during the years 1955, 1959 and 1960). This period includes the anomalously wet conditions from 1961 to 1963 when the level

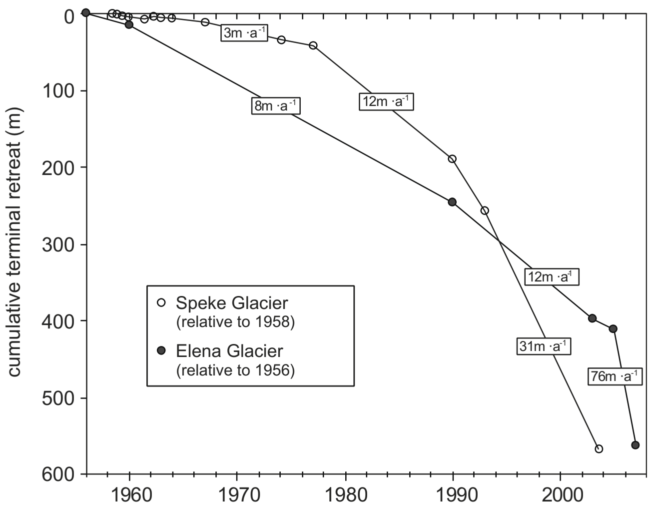

Fig. 4. Observed retreat in the terminal positions of the Speke and Elena glaciers relative to observations in 1958 and 1956, respectively. Data derive from Kaser and Osmaston (2002), Whittow et al. (1963) and this work.

of Lake Victoria and the River Nile in Uganda rose by 2.5 m (Lamb, 1966; Kite, 1981). As a result, the mean discharge of the River Mubuku over this period may slightly exceed the long-term mean. Based on a complete record of observations in 2000 for a slightly smaller catchment area (246 km^2) gauged at Bugoye (station 8 in Fig. 3), mean discharge of the River Mubuku is 12 $m^3\ s^{-1}$. Over the period between these observations, no significant temporal trends (at a 95% confidence interval) in precipitation are evident from records at Kilembe (1949–1998) and Kasese (1964–2006) (stations 9 and 10 in Fig. 3). The mean specific discharge of the River Mubuku from 1954 to 1965 is 1730 mm a^{-1}, more than three times that of the River Nyamagasani (493 mm a^{-1}) to the south (Fig. 3) over the same period. As the River Mubuku is the primary catchment still to have its headwaters supplied by glacial meltwaters, the presumption that a substantial proportion of the river's discharge derives from glacial meltwater discharges (e.g. Uganda Meteorology Department, 2006) likely derives from its disproportionately high specific discharge. Spot measurements of alpine riverflow summarised in Fig. 7 and Table 1, challenge this assumption.

Measured glacial meltwater fluxes down gradient from the Speke Glacier (station 1, Fig. 1), the largest valley glacier in the Rwenzori Mountains, on 28 January 2005 (dry season) and 21 April 2007 (wet season) are 0.002 and 0.017 $m^3\ s^{-1}$, respectively. Measurements were taken during the late afternoon (3–4 pm) when meltwater discharges are generally highest and follow by 1–3 h diurnal maxima in temperature and insolation (Whittow et al., 1963). Our

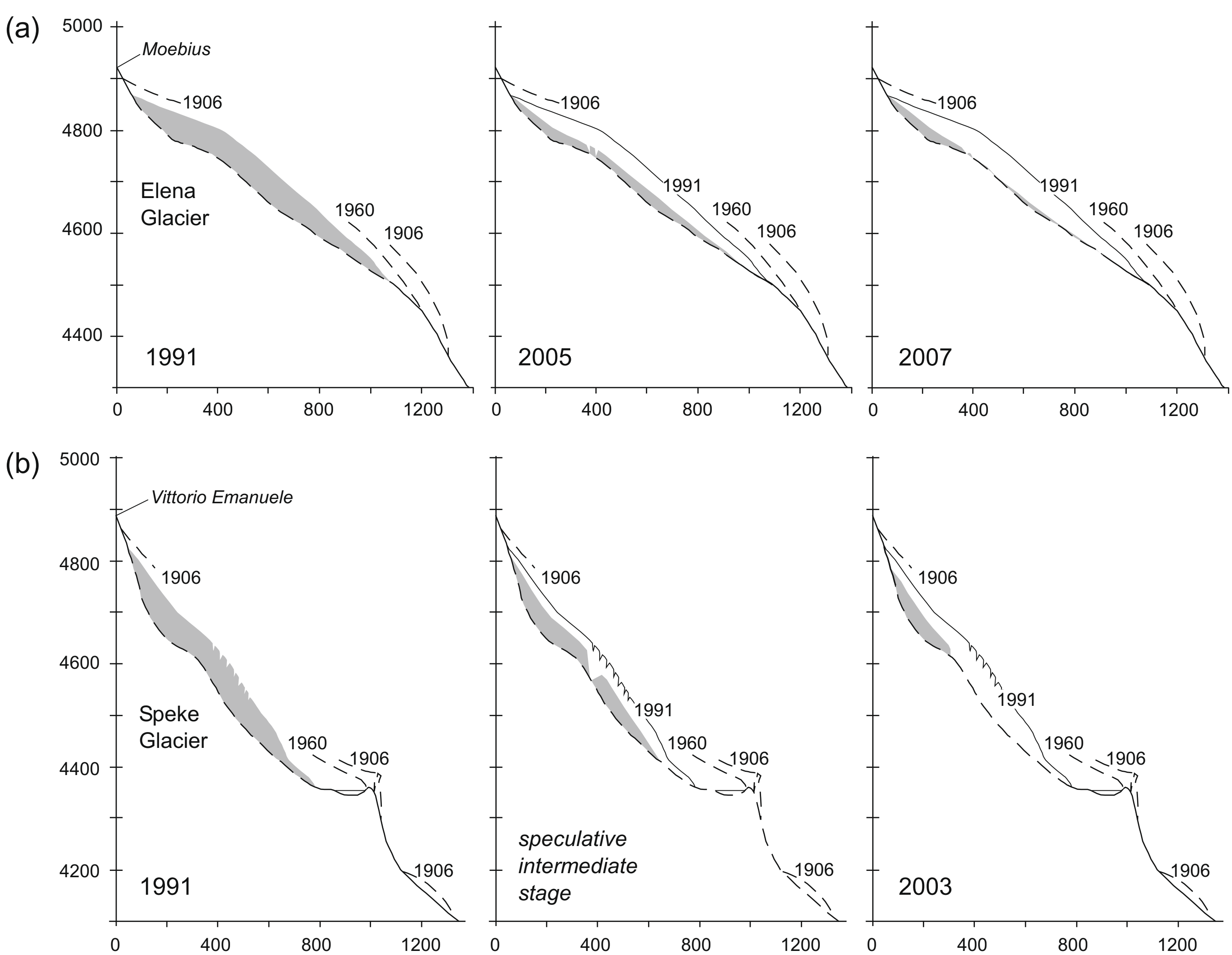

Fig. 5. A schematic, cross-sectional representation of changes in the profiles of 'indicator' valley glaciers (shaded): (a) Speke and (b) Elena in the Rwenzori Mountains from 1991 to 2005 [adapted from Kaser and Osmaston (2002)]. Glacial thickness and bed topography are not known precisely. Vertical exaggeration is × 2.

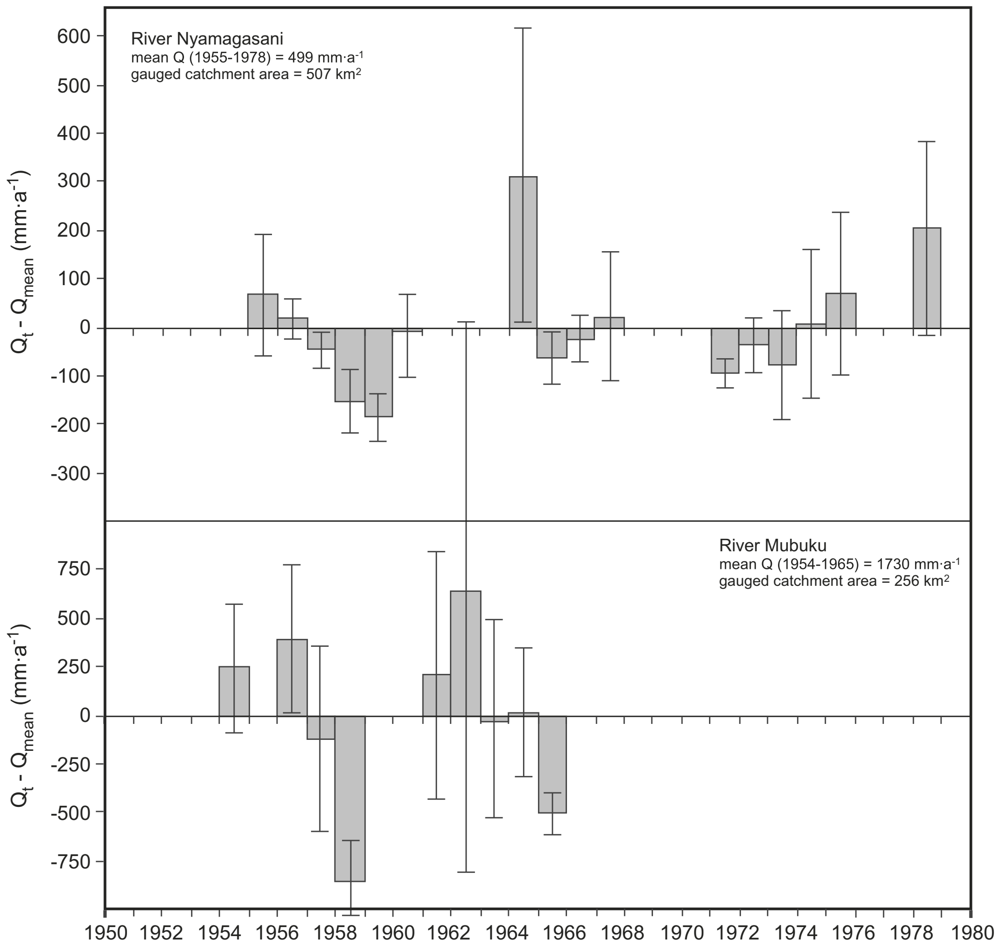

Fig. 6. Longitudinal trends in deviations from mean riverflow observed at the base of the Rwenzori Mountains from 1952 to 1978. Missing data for the Rivers Mubuku and Nyamagasani reflect incomplete discharge records for these calendar years. Calculated errors derive from uncertainty in the derivation of the rating curve.

spot observations are generally consistent with, but slightly lower than, historical data from Whittow et al. (1963) who observed a mean meltwater discharge of 0.019 $m^3 s^{-1}$ over a 12-day period during the dry season in 1959. Assuming that our observations are within an order of magnitude of the seasonal mean flux, these fluxes represent between 0.01% and 0.2% of the mean discharge of the River Mubuku recorded at the base of the Rwenzori Mountains (station 7 in Fig. 3) during the dry season (10 $m^3 s^{-1}$) and wet season (18 $m^3 s^{-1}$), respectively. Cumulative meltwater discharges from approximately half of the remaining icefields in the Rwenzori Mountains to the River Mubuku together with contributions from a non-glaciated catchment area of 4.9 km^2 are aggregated at Lake Bujuku (Fig. 1c). Spot measurements of the discharge at the lake's outlet (station 2 in Fig. 1c) during the dry and wet season constitute between 0.5% and 2% of the river's mean discharge (Fig. 7). With an estimated annual precipitation of 2000 mm a^{-1} at Lake Bujuku (Fig. 2), meltwater contributions from glaciers necessarily amount to considerably less than the measured outflow from Lake Bujuku (0.06–0.30 $m^3 s^{-1}$) and are expected to be <0.5% of the river's discharge at the base of the mountain even if limited glacial meltwater contributions from Mount Baker (site 5, Fig. 3) as well as the Vittorio Emanuele and Johnston glaciers on Mount Speke are considered.

The discharge profile of River Mubuku (Fig. 7) reveals a substantial increase in discharge below the glaciers in the Heath-moss forest zone (3000–4000 mamsl) where the catchment area expands from 15% to 46% and precipitation is highest (2600 mm a^{-1}). Hypsographic curves of catchment area for the Rivers Mubuku and Nyamagasani basins (Fig. 6) show that >70% of the River Mubuku basin resides within the Montane forest, Heath-moss forest and Afroalpine ecotones where mean annual precipitation exceeds 2000 mm a^{-1}. In comparison, >70% of the River Nyamagasani basin lies below these ecotones within the grasslands where mean annual precipitation is 1150 mm a^{-1}. The relatively higher proportion of orographic precipitation that falls in the River Mubuku basin (mean catchment P = 2030 mm a^{-1}), compared with the River Nyamagasani basin (mean catchment P = 1540 mm a^{-1}), accounts, in part, for observed differences in river discharge. As more than half of the River Mubuku basin lies above 2800 mamsl where observed water temperatures are ~10 °C and more than half of the River Nyamagasani lies below 1500 mamsl where water temperatures are ~17 °C, proportionately greater evaporative losses in the River Nyamagasani are also expected to account for some of the difference in the mean discharge between these neighbouring catchments.

The negligible contribution of glacial meltwaters to alpine riverflow deduced in the Rwenzori Mountains is expected to apply to other tropical alpine catchments where glaciers occupy a tiny proportion (<1%) of the basin area (i.e. Irian Jaya, Kilimanjaro, Mount Kenya). On Kilimanjaro, Hemp (2005) cites an unpublished estimate of an annual meltwater discharge of $10^6 m^3 a^{-1}$ (~0.03 $m^3 s^{-1}$) from the Southern Icefields that are similar in size (~1.3 km^2) to the Rwenzori icefields. Reported reductions in dry-season riverflow on Kilimanjaro (Desanker, 2002) are, therefore, likely to derive from declining rainfall and changes in land use. Hemp (2005) reports declining lowland precipitation of between 27% and 38% over the last century for three stations around the

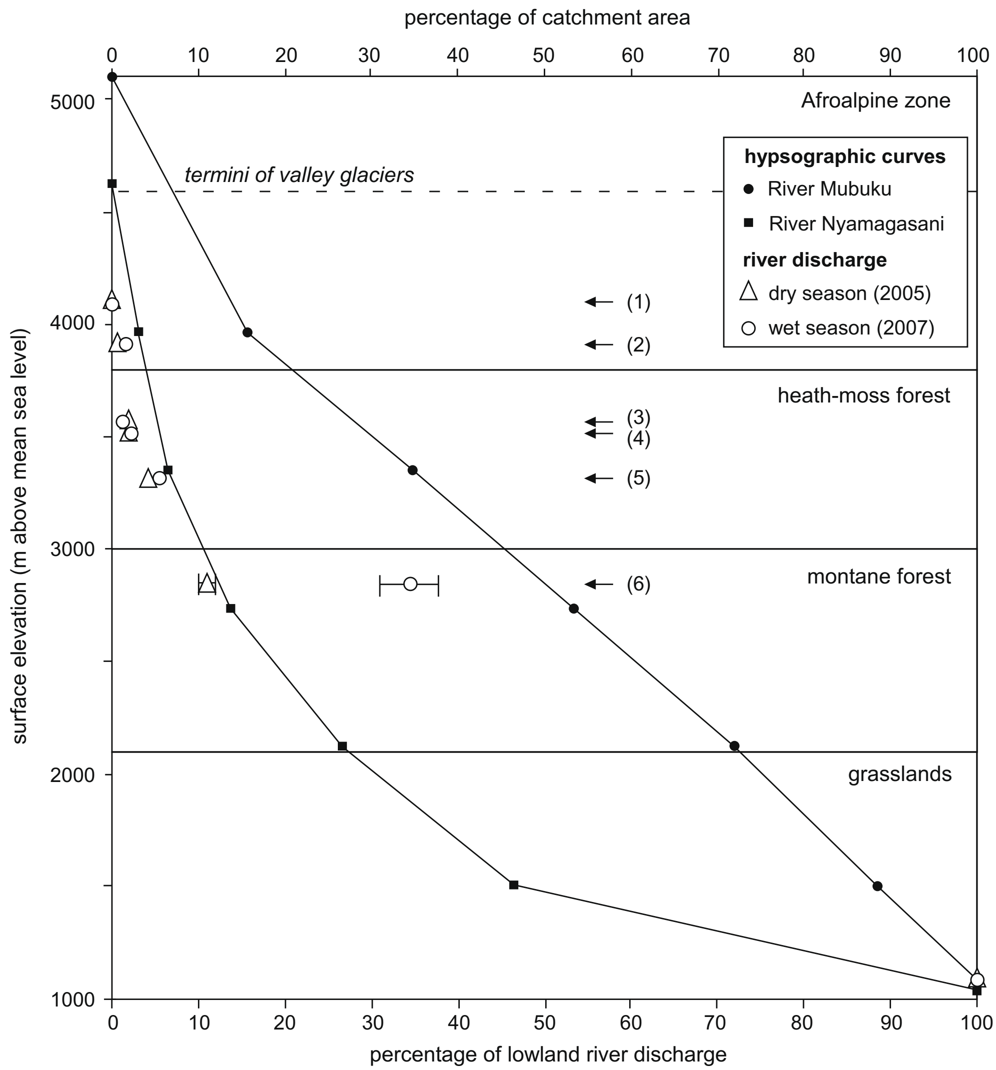

Fig. 7. Spot measurements of river discharge during the dry season (2005) and wet season (2007) as a percentage of mean discharge for the dry season (February, 1954–1965) and wet season (October, 1954–1065); hypsographic curves for the Rivers Mubuku and Nyamagasani are plotted along the same ordinate axis. The number of each river discharge measurement station (locations in Figs. 1 and 3) is given in parentheses by elevation.

Table 1
Spot measurements of surface discharge (*Q*) in the River Mubuku basin together with the proportion of the catchment covered by glaciers. Site locations in parentheses are shown in Figs. 1 and 3.

Tributary (site)	Elevation (mamsl)	*Q* (dry)[a] ($m^3\ s^{-1}$)	*Q* (wet)[b] ($m^3\ s^{-1}$)	Catchment area (km^2)	*Q* (dry)[a] ($mm\ a^{-1}$)	*Q* (wet)[b] ($mm\ a^{-1}$)	Glacial[c] area (%)
Speke (1)	4104	0.002	0.017	0.6	89	890	33
Bujuku (2)	3918	0.06	0.30	5.3	360	1800	8.1
Bujuku (3)	3520	0.18	0.43	9.6	590	1400	4.5
Bujuku (4)	3321	0.41	1.0	32.6	400	970	1.3
Mubuku (5)	3580	0.20	0.22	10.0	630	690	1.7
Mubuku (6)	2845	1.1	6.2	35.0	990	5600	0.5
Mubuku (7)[d]	1095	*10*	*18*	256	*1280*	*2230*	0.2

[a] January 25–February 2, 2005.
[b] April 20–24, 2007.
[c] 2003 (Taylor et al., 2006a).
[d] Mean dry *Q* (February, 1954–1965), mean wet *Q* (October, 1954–1965).

base of Kilimanjaro (Moshi, Kilema Mission, Kibosho Mission). In contrast, analysis of lowland (<2000 mamsl) records of precipitation in western Uganda (Fig. 1a) over the 20th century fails to detect significant downward trends (Fig. 8). Small but statistically significant trends of increasing precipitation (at a 95% confidence interval) are observed at Fort Portal (1903–1978) and Mbarara (1904–1999). On Kilimanjaro, rapid loss of montane and cloud forest has also reduced both fog interception and canopy water storage (Hemp, 2005). In contrast, deforestation within catchments downslope of the icefields on the Rwenzori Mountains has largely been prevented as land above 1700 mamsl has been protected from encroachment through its designation as a National Park and World Heritage Site in 1991 (Osmaston, 2006) and, prior to this, as a forest reserve.

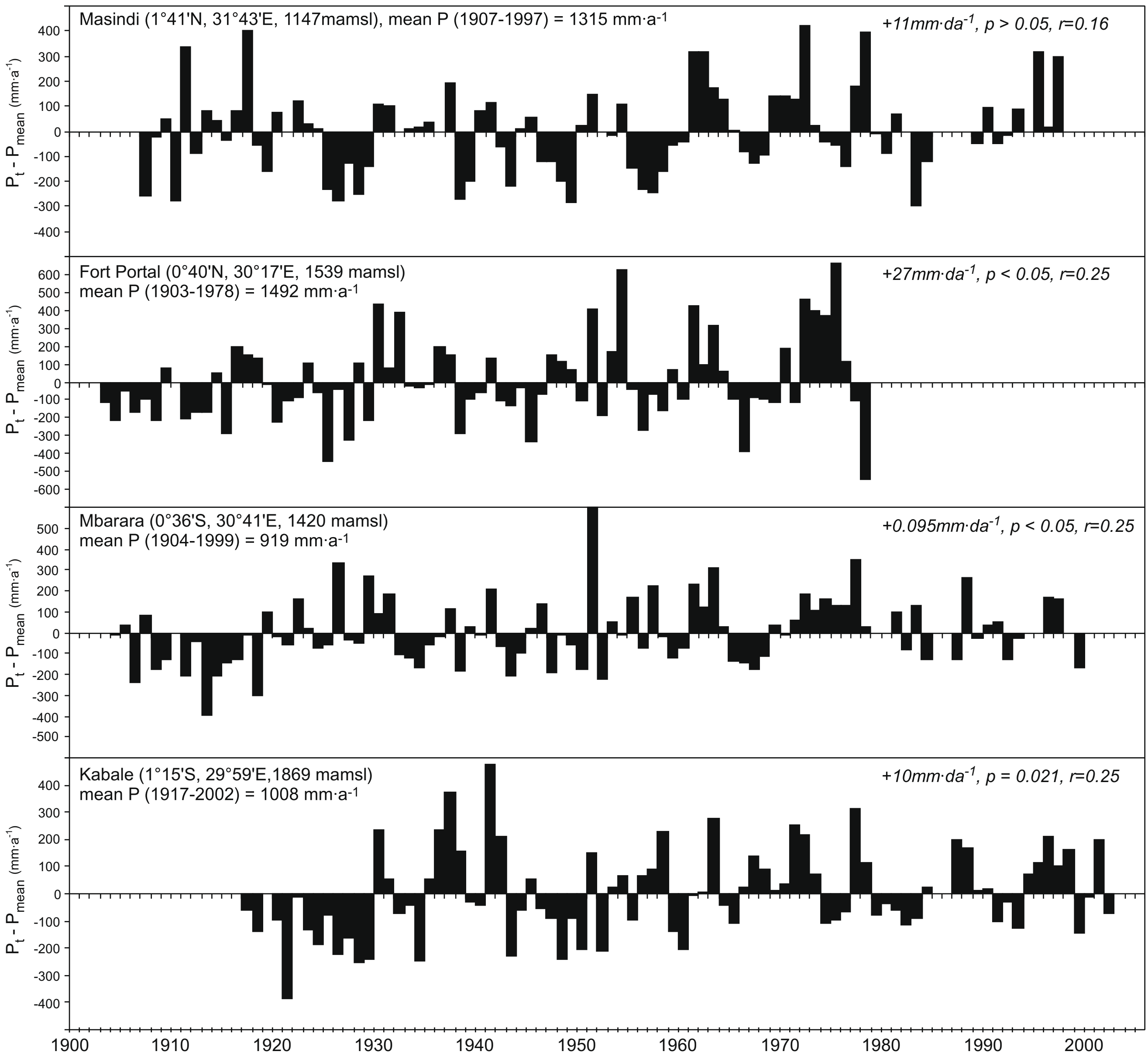

Fig. 8. Longitudinal trends in annual precipitation, plotted as deviations from the mean, for regional meteorological stations in western Uganda over the 20th century.

5. Conclusions

Glaciers in the Rwenzori Mountains continue to recede rapidly. Observed acceleration in the rates of termini retreat of two valley glaciers since the late 1960s is attributed, in part, to the convex–concave slope profile in which the valley glaciers reside. Current glacial recession has a negligible impact on alpine riverflow. Spot measurements of meltwater discharges indicate that icefields contribute considerably less than 2% of the total discharge of the principal river receiving meltwater discharges (River Mubuku) at the base of the Rwenzori Mountains during both dry and wet seasons. The anomalously high specific discharge of the River Mubuku (1730 mm a^{-1}) arises from high rates of precipitation (2340–2600 mm a^{-1}) below alpine icefields within Heath-moss and Montane forest ecotones that occupy more than half of the river's gauged catchment area. Our conclusion in the Rwenzori Mountains that glacial meltwater discharges contribute negligibly to alpine riverflow is expected to apply to other tropical alpine glaciers outside of the South American Andes (i.e. Irian Jaya, Kilimanjaro, Mount Kenya) where icefields represent a tiny fraction (<1%) of alpine river catchment areas.

Acknowledgements

Research was made possible by grants from the Royal Geographical Society (EPSRC Small Research Grant 01/07, Ralph Brown Ward 2003) and The Royal Society (SLP/15681). Research was conducted with permission of the Ugandan National Council of Science and Technology (No. NS 145) and Uganda Wildlife Authority (UWA). The authors are grateful for field assistance provided by the Rwenzori Mountaineering Service and Nelson Guma (UWA).

References

Bergstrøm, E., 1955. British Ruwenzori Expedition, 1952: glaciological observations – preliminary report. Journal of Glaciology 2, 468–473.
Bradley, R.S., Vuille, M., Diaz, H.F., Vergara, W., 2006. Threats to water supplies in the Tropical Andes. Science 312, 1755–1756.
Day, T.J., 1976. On the precision of salt dilution gauging. Journal of Hydrology 31, 293–306.

Desanker, P., 2002. Impact of climate change on life in Africa. Report to the World Wildlife Fund Climate Change Program (Washington), p. 6.

Gasse, F., 2002. Palaeoclimate: Kilimanjaro's secrets revealed. Science 298, 548–551.

Hastenrath, S., 1984. The Glaciers of Equatorial East Africa. Reidel, Dordrecht. p. 353.

Hastenrath, S., 2001. Variations of East African climate during the past two centuries. Climatic Change 50, 209–217.

Hemp, A., 2005. Climate change – driven forest fires marginalise the impact of ice cap wasting on Kilimanjaro. Global Change Biology 11, 1013–1023.

Kaser, G., Noggler, B., 1991. Observations of Speke Glacier, Ruwenzori Range, Uganda. Journal of Glaciology 37, 313–318.

Kaser, G., Noggler, B., 1996. Glacier fluctuations in the Ruwenzori Range (East Africa) during the 20th century – a preliminary report. Zeitschrift für Gletscherkunde und Glazialgeologie 32, 109–117.

Kaser, G., Osmaston, H.A., 2002. Tropical Glaciers. Cambridge University Press, Cambridge. p. 207.

Kaser, G., Hardy, D.R., Mölg, T., Bradley, R.S., Hyera, T.M., 2004. Modern glacier retreat on Kilimanjaro as evidence of climate change: observations and facts. International Journal of Climatology 24, 329–339.

Kite, G.W., 1981. Recent changes in level of Lake Victoria. Hydrological Science Bulletin 26, 233–243.

Lamb, H.H., 1966. Climate in the 1960s. Geographical Journal 132, 183–212.

Lands and Surveys Department Uganda, 1961. Fort Portal Sheet NA-36-I3 (1:250,000).

Mark, B.G., Seltzer, G.O., 2003. Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca Peru. Journal of Glaciology 49, 271–281.

Mark, B.G., McKenzie, J.M., Gómez, I.J., 2005. Hydrochemical evaluation of changing glacier meltwater contribution to stream discharge: Callejon de Huaylas, Peru. Hydrological Science Journal 50, 975–987.

Menzies, I., 1951. Some observations on the glaciology of the Ruwenzori Range. Journal of Glaciology 1, 511–512.

Mölg, T., Georges, C., Kaser, G., 2003. The contribution of increased incoming shortwave radiation to the retreat on the Rwenzori glaciers, East Africa, during the 20th century. International Journal Climatology 23, 291–303.

Mölg, T., Rott H., Kaser G., Fischer A., Cullen N.J., 2006. Comment on recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature. In: Taylor, R.G., Mileham, L.J., Tindimugaya C., Majugu A., Muwanga A., Nakileza N. (Eds.), Geophysical Research Letters, vol. 33, p. L20404.

Nicholson, S.E., Yin, X., 2001. Rainfall conditions in equatorial East Africa during the nineteenth century as inferred from the record of Lake Victoria. Climatic Change 478, 387–398.

Okunishi, K., Saito, T., Yoshida, T., 1992. Accuracy of stream gauging by dilution methods. Journal of Hydrology 137, 231–243.

Osmaston, H.A., 1989. Glaciers, glaciations and equilibrium line altitudes on the Rwenzori. In: Mahaney, W.C. (Ed.), Quaternary and Environmental Research on East African Mountains. Balkema, Rotterdam.

Osmaston, H.A., 2006. Guide to the Rwenzori. The Rwenzori Trust (Ulverston).

Osmaston, H.A., Kaser, G., 2001. Rwenzori Mountains National Park, Uganda and Parc National des Virungas, Democratic Republic of Congo Glaciers and Glaciations. WWF (ISBN: 0-95180394-8).

Russell, J., Eggermont, H., Taylor, R.G., Verschuren, D., 2008. Paleolimnological records of recent glacial recession in the Rwenzori Mountains, Uganda-DR, Congo. Journal of Paleolimnology. doi:10.1007/s10933-008-9224-4.

Talks, A., 1993. East African Hot Ice 1993. Internal Report – Sir Roger Manwood's School, Kent (UK) to Royal Geographical Society (UK).

Taylor, R.G., Aggrey, K., 2004. Review of river discharge records and gauging stations in the Rwenzori Mountains of Uganda. Unpublished Report to Water Resources Management Department (Entebbe), p. 16.

Taylor, R.G., Howard, K.W.F., 1998. Post-palaeozoic evolution of weathered landsurfaces in Uganda by tectonically controlled cycles of deep weathering and stripping. Geomorphology 25, 173–192.

Taylor, R.G., Mileham, L.J., Tindimugaya, C., Majugu, A., Muwanga, A., Nakileza, N., 2006. Recent recession in the Rwenzori Mountains of East Africa due to rising air temperature. Geophysical Research Letters 33, L10402.

Temple, P.H., 1968. Further observations on the glaciers of the Ruwenzori. Geografiska Annaler A 50, 136–150.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Henderson, K.A., Brecher, H.H., Zagorodnov, V.S., Mashiotta, T.A., Lin, P.-N., Mikhalenko, V.N., Hardy, D.R., Beer, J., 2002. Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa. Science 298, 589–593.

Uganda Meteorology Department, 2006. Climate Change: Uganda's National Adaptation Programmes of Action. Report to United Nations Environment Programme, p. 94.

Whittow, J.B., Shepherd, A., Goldthorpe, J.E., Temple, P.H., 1963. Observations on the glaciers of the Rwenzori. Journal of Glaciology 4, 581–615.