Glacier Runoff Modelling

Using data collected on the Passu Glacier in the Karakoram Himalaya,Paksitan during the summer of 1997 a glacier runoff model was created to enable prediction of dishcangre from glacier meltwater. Figure 1 shows the Passu Glacier flowing down towards the settlement of Pasu. The larger Baltura Glacier lies to the north.

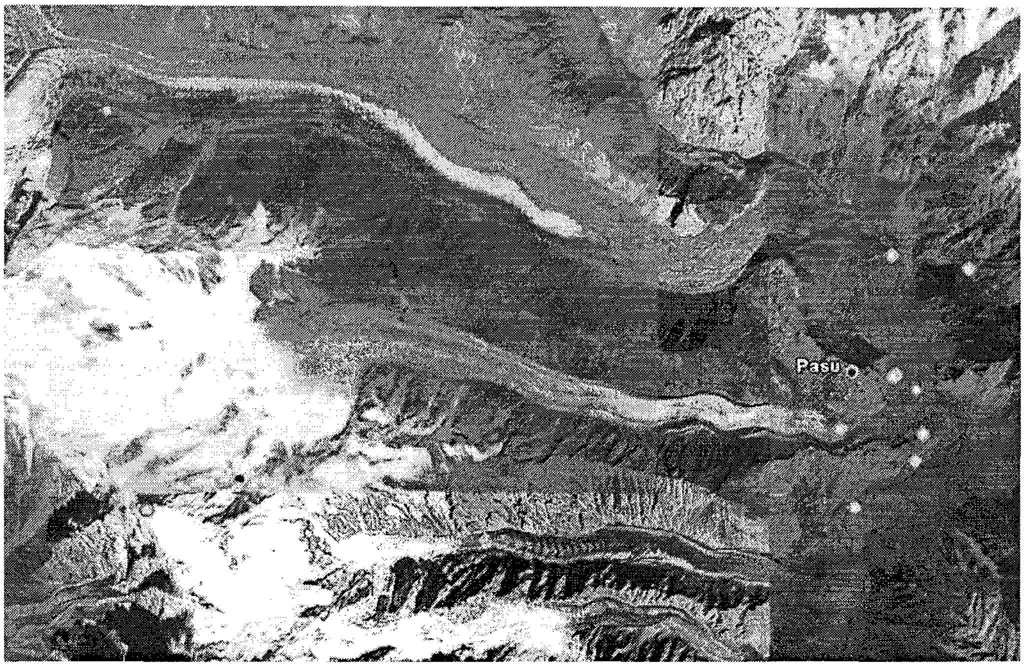


Figure 1 - Satellite image of the Passu Glacier (Digital Globe, 2007)

—×— air temperature —— instantaneous Q —— Q 4 hour lag —— 4 hour lag + storage —— observed Q

Figure 1 - Legend for all graphs used in the report

Q2 - The effect of altering model parameters on discharge rates

Adjusting Degree Day Factors

When the degree day factor for snow was increased, thepercentage of positive degree days also increased leading to greater melt rates. When the same was done for the degree day factor of ice a similar relationship was observed. However, as ice has a lower albedo than snow, a smaller percentage of solar radiation was reflected by the ice meaning that the runoff model predicted a greater discharge due to the higher amount of solar energy in the system that was causing melt (Benn and Evans, 2005). The inverse of this relationship was observed when the degree day factors for snow and ice were decreased.

Another important observation was that the adjutsments made to the degree day factor of ice ~~made~~ had little or no impact ~~to~~ on the discharge when the snowline was below 6500m. This was because a snowline at the lower points of 2500m and 4501m implies that the majority of the surface cover is snow leaving the melt of ice at the surface as a minimal factor.

Adjusting Lapse Rate

The thermal energy of an air mass is proportional to its density menaing that air temperature decreases with barometric pressure causing a lapse rate (Benn and Evans, 2005). When the lapse rate was increased in this model dishcarge fell dramatically with the only readings predicted being associated with the maximum ~~temperature~~ diurnal melt on the given days. When lapse rate was decreased the model predicted increased discharge as the temeporature gradient was shallower.

Adjusting Snow Line Elevation

As the transient snowline moves up glacier the snow covered area decreases due to increased melting and the underlying bare ice is exposed. The lower albedo of this ice combined with the melt from the snow means that the overall production of meltwater is increased dramamtically (Lowe and Collins, 2001).

Q3 – Mid summer predicticed run-off model

DDF Snow = 0.4

DDF Ice = 0.6

Lapse rate = 0.2

Snow Line Elevation = 4501m

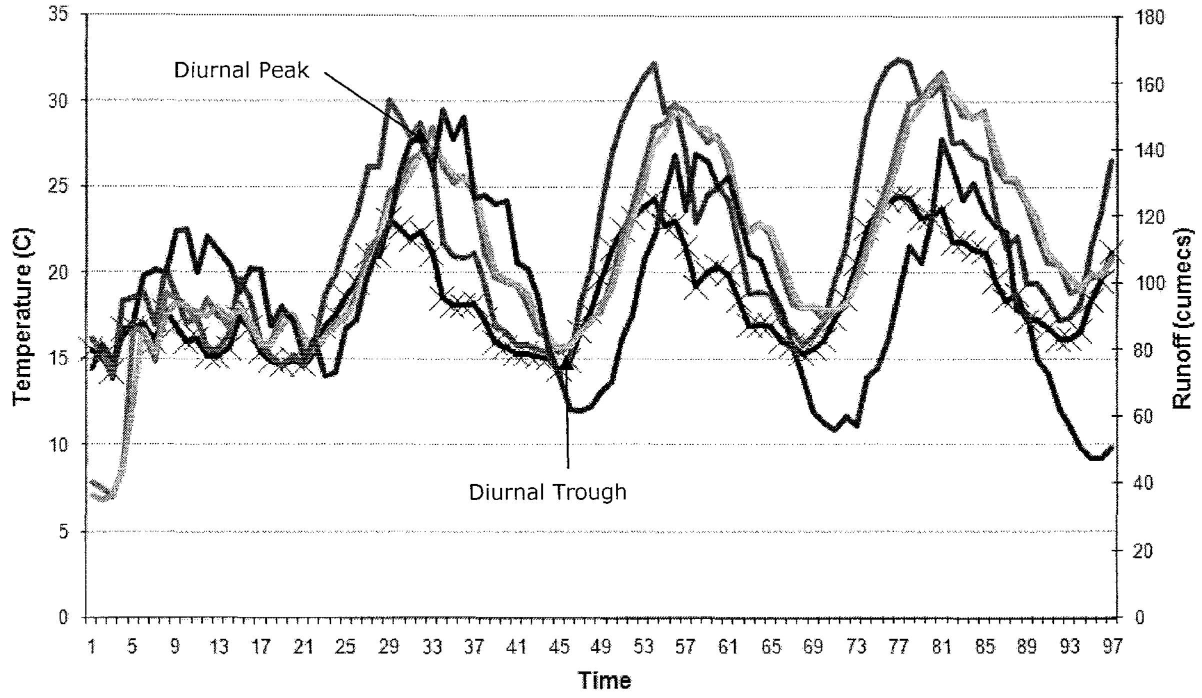
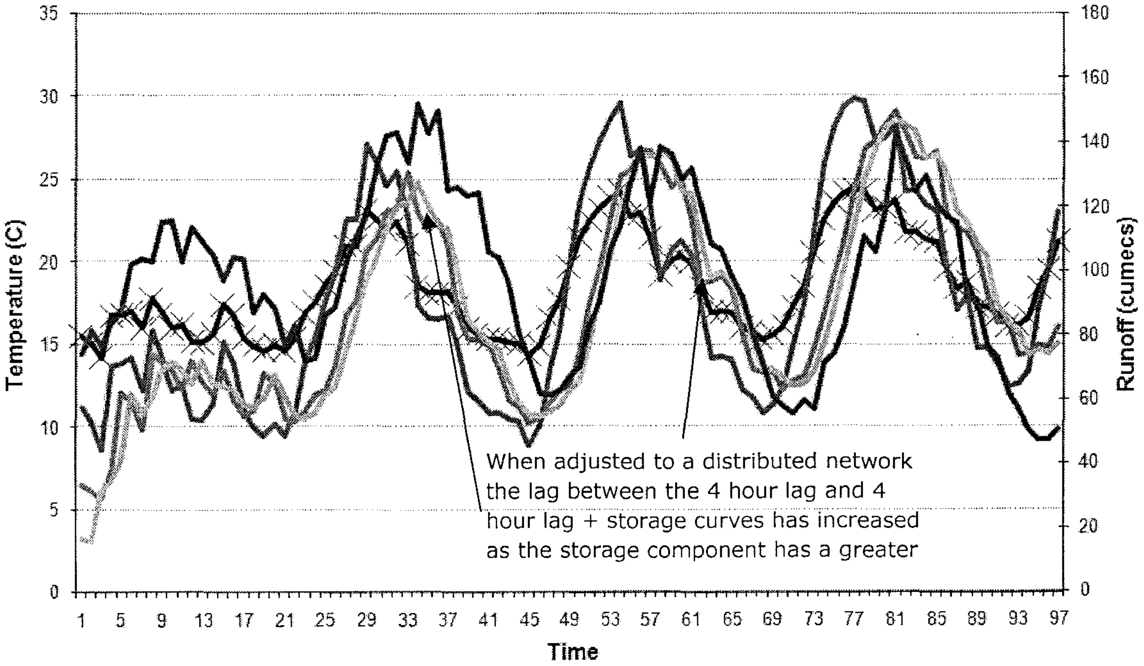


Figure 2 – Best fit graph between observed and predicted runoff on the Passu Glacier during mid-summer

Q4 The effect on predicted runoff from a Distributed Drainage Network in mid-summer



When adjusted to a distributed network the lag between the 4 hour lag and 4 hour lag + storage curves has increased as the storage component has a greater

Figure 3 – Runoff model showing a distributed drainage network in mid-summer

Degree Day Factor Snow - 0.5

Degree Day Factor Ice - 0.6

Lapse Rate - 0.3

Snow Line Altitude – 4501m

K1 - 0.5

K2 - 0.3

K3 - 0.2

KS1 - 0.5

KS2 - 0.7

KS3 - 0.8

A distributed drainage system is predominantly a cavity linked network in which drainage of meltwater will be inefficient due to the poorly connected system (Benn and Evans, 2005). When the storage co-efficients of the model were adjusted to represent a distributed network a greater difference between the four hour lag and four hour lag plus storage was observed. The storage aspect accounts for the inefficient nature of the drainage system creating a lag. Re word

Q5 What might the observed runoff response from a rainfall event effect tell us about the subglacial hydrological system beneath the Passu Glacier in July 1997?

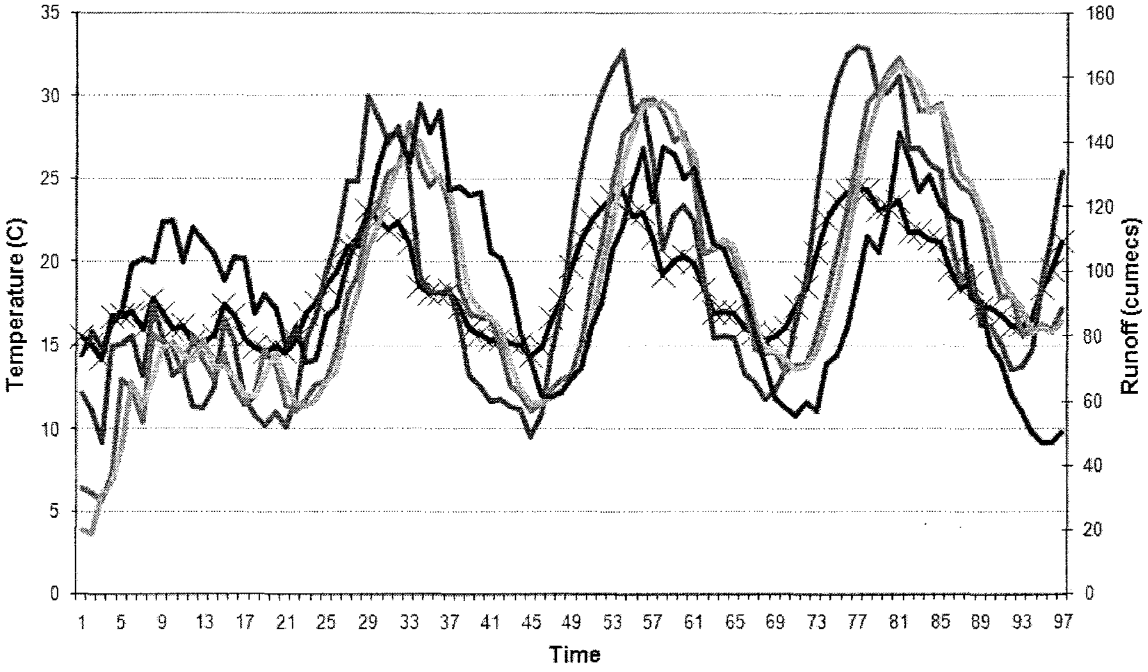


Figure 4 – Runoff model in 11th July without rainfall event data

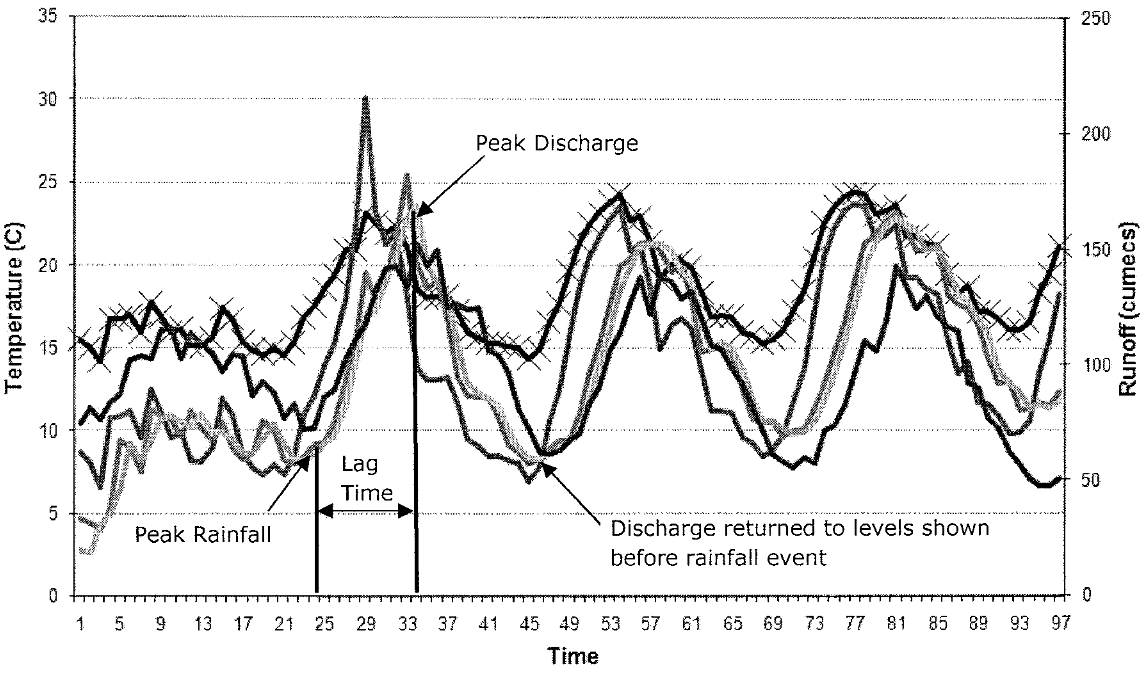


Figure 5 - Runoff model in 11th July after a rainfall event

The Passu Glacier is most likely to be a summer accumulation type glacier as it is part of the high altitude, Himalayan mountain range. In these types of glacier maximum accumulation and ablation occurs almost simultaneously during the summer months (Benn and Evans, 2005). The subglacial drainage network although not fully developed by July will be predominantly discrete in form leading to rapid discharge and minimal storage at the glacier snout.

A rainfall event is observed 24 hours into the data gathering commencing at 12:00 and finishing at 16:00 on the 11th July. Figures 4 and 5 show the predicted discharge from the glacier before and after the rainfall event. Following the rain fall event the peak discharge for the 11th July remains at approximately 18:00 but the volume of meltwater has increased from approximately 140 cumecs to 175 cumecs. This indicates that prior to the rainfall event, the drainage network was not operating at full capacity because as the flow increased, the network was able to discharge a grater volume within the same time frame.

By the next diurnal minimum discharge at approximately 05:00 on 12th July the discharge has returned to pre-rainfall predicted levels of approximately 50 cumecs which suggests that the subglacial drainage network has almost fully recovered from the rainfall event. This confirms that the subglacial drainage network predominantly is discrete in form as storage components seem to have had little or no affect on discharge compared to the pre rainfall event model.

Q6 – What glaciological data would improve the model?

Implementation of parts of the HBV-ETH model could also enhance the model. Simplified elevation zones are given a further degree of complexity by the addition of aspect classes which can account for variation of melt on south and north facing slopes (Hock, 2003). This aspect factor was also adopted by Dunn and Colohan (1999, cited in Hock, 2003) in which the basin was divided into five slope elevations and three aspect classes.

detail

Remote sensing also enables mapping of debris covered areas of the glacier. Debris covered surfaces have a lower albedo than that of snow and ice therefore they absorb more short wave radiation and heat up whilst emitting ~~more~~ long wave radiation and causing greater ablation rates to surrounding snow and ice (Benn and Evans, 2005).

Further improvements could be made by an accurate topographical measurement of snowpack depth. Most models assume that uniform melt occurs over a non-uniform depth within each elevation zone (Turpin, Ferguson and Clark, 1997) meaning that estimates will not always be reliable.

Q7 – What meteorological data would improve the model?

The first stage of runoff modelling is to extrapolate the necessary meteorological data that is to be used by the model (Ferguson, 1999). A wider array of meteorological inputs would enhance such models to provide a more reliable result.

Degree Day Factors vary seasonally due to the variation of clear-sky direct radiation throughout the year (Hock, 2005). Therefore an input for solar radiation would be a useful addition to the model. Closely linked to this is cloud cover data which affects surface albedo. Snow albedo has been observed to increase by up to 15% when overcast conditions prevail in glacial climates (Holmgren, 1971; Greuell and Oerlemans, 1987, cited in Hock, 2005).

Wind measurements would also improve the effectiveness of the model. Yang *et al.*, (1998, cited in Daly, Davis, Ochs and Pangburn, 2000) observed that during high winds, gauges underestimated precipitation rates, especially in exposed areas. leading to inaccuracies in measurements

Identifying precipitation type is also important to the model. Most meltwater models use air temperature extrapolated from a base station to determine whether precipitation takes the form of snow or ice (Ferguson, 1999). For greater spatial resolution of data such as precipitation and lapse rate, a larger network of climate monitoring stations could be used so that data can be measured rather than extrapolated. The model currently uses data collected from the climate station at 2500m and extrapolates this data across the whole system meaning that the model is biased towards one part of the glacier (Ferguson, 1999).

Figure 6 shows the interlinked relationship between extrapolated meteorological data, snow melt and snowpack parameters when predicting runoff volumes.

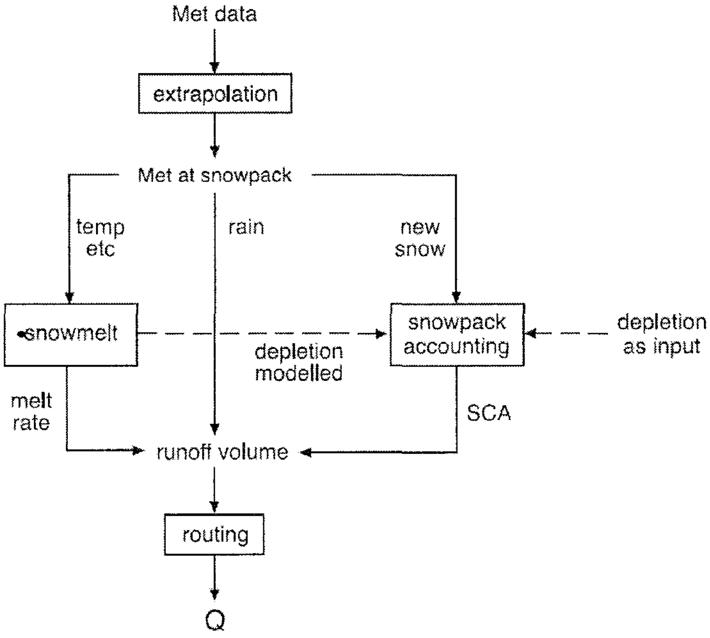


Figure 6 – Meteorological inputs to snowmelt modelling

Q8 – What simple map based exercise would enhance the model and improve its accuracy?

Remote sensing is a key tool for creating maps to enhance runoff models. Satellites such as Landsat have the necessary spatial and spectral resolution to map areas of exposed ice and snow covered areas to apply appropriate degree day factors to runoff models (Schaper, Martinec and Seidel, 1999).

Remote sensing allows for a topographical study of the glacier surface which has major implications for melt in terms of slope angle, aspect and shading (Hock, 2003). This is also an important factor when estimating the total volume of new meltwater as the topographic study will identify areas of spatial variability within the snowpack due to hollows or peaks (Ferguson, 1999).

The model used for this practical divides the glacier into three elevation zones. These zones cover thousands of square metres of ice and snow cover. More precise mapping of zones every 1000m for example would enhance the model. Further improvement could be made by replacing theoretical snowline elevation zones with transient snowline heights from classified satellite scenes (Turpin *et al.*, 1997). However, satellite data can be limited due to low repetition rates and potential cloud cover (Blöschl and Kirnbauer, 1992, cited in Turpin *et al.,* 1997).

Q9 Techniques for predicting runoff from glacierised basins

Glacierised runoff is one of the most complex runoff processes to model accurately (Jones, 1997) with the field experiencing a gradual change in the use of prediction techniques. It is important to understand the processes involved with glacier runoff as the water resources that result can affect public supply, hydroelectric power and irrigation (Ferguson, 1999). Runoff models generally fall into two classes: temperature index (degree day) models and energy balance models (Hock, 2003).

Temperature index models

This type of model was first used by Finsterwalder and Schunk in 1887 and has since been modified and refined by worldwide scientists (Hock, 2003) to show the empirical relationship between melt rate and air temperature (Jones, 1997). The model takes a 'black box' approach in which the inputs and outputs to the system are observed but the processes in the englacial and subglacial environments are unknown. Hock (2003) identifies four reasons why the temperature index model has had such longevity:

- Wide availability of air temperature data
- Ease of interpolating and forecasting air temperature data
- Good model performance despite simplistic approach
- Computational simplicity

Degree day models can be adjusted by increasing the number of variables such as solar radiation inputs leading to a gradual transition towards energy balance models.

Temperature is most reliable meteorological variable across glacierised basins so this particular method of modelling lends itself to accurate modelling of melt volumes even though it is of low complexity. (Ferguson, 1999). However, with the addition of more variables, this approach is being gradually modified to create more complex energy balance models (Hock, 2003).

Energy Balance Models

Assessment of energy fluxes between the glacier surface and the atmosphere forms the basis of these types of models (Hock, 2005). The energy balance components can be expressed by the following equation:

$$Q_N + Q_H + Q_L + Q_G + Q_R + Q_M = 0$$

The symbols are as follows: Q_N is net radiation, Q_H is sensible heat flux, Q_L is latent heat flux, Q_G is ground heat flux, Q_R is sensible heat flux supplied by rain and Q_M is energy consumed by melt (Hock, 2005). The zero result represents equilibrium but positive outcomes would signify an energy gain and negative outcomes an energy loss (Hock, 2005). The importance of each component varies temporally and spatially. For example, sensible heat transfer is important during periods of cloud cover, rain and high wind speed (Hock, 2003).

Net radiation is a key aspect of the energy balance model. Solar radiation varies greatly in time and pace in mountainous regions due to factors such as slope, aspect and effective horizons. The primary issue is that these factors affect the amount of short wave radiation that reaches the glacier surface by obscuring the path it takes. (Hock, 2005).

The turbulent fluxes of sensible and latent heat within the model are affected by the temperature and moisture gradient at the boundary between air and the glacier surface (Hock, 2005). Latent heat flux in particular greatly affects melt rates on temperate glaciers (Lang, 1981, cited in Hock, 2005) but accurate measurements require sophisticated instruments and continuous maintenance causing major logistical problems for researchers (Hock, 2005).

As previously mentioned each component of the energy balance model varies temporally and spatially but it is the size if this variation which proves to be an obstacle when undertaking research (Ferguson, 1999).

In the modern era, remote sensing has become a vital technique used to enhance runoff models. Accurate modelling of transient snowlines and topographic elevations has led to improved confidence in the reliability of runoff predictions (Turpin *et al.*, 1997) and these are likely to become even more reliable in the future as resolutions become more detailed.

Conclusion

The relatively simple temperature index model has been the predominant method of modelling glacierised runoff over the past 50 years and it is now suggested that more complex energy balance models should replace it. However, the temperature index model remains effective and popular among scientists due to its simplicity and logistical ease (Rango and Martinec, 1995). Energy balance models, although potentially more accurate are impractical due to large data requirements and spatial variability required (Hock, 2003).

References

Benn, D.I., and Evans, D.J.A. (2005). *Glaciers and Glaciation*. Arnold: London

Daly, S.F., Davis, R., Ochs, E. and Pangburn, T. (2000). An approach to spatially distributed snow modelling of the Sacramento and San Joaquin basins, California. *Hydrological Processes, 14*, 3257–3271.

Digital Globe. (2007). *Google Earth Image*. Retrieved 01 December, 2007

Hock, R. (2003) Temperature index melt modelling in mountain areas. *Journal of Hydrology, 282*, 104-115.

Hock, R. (2005) Glacier melt: a review of processes and their modelling. *Progress in Physical Geography, 29*(3), 362-391

Ferguson, R.I. (1999). Snowmelt runoff models. *Progress in Physical Geography, 23*(2), 205-227.

Jones, J.A.A. (1997). *Global Hydrology*. Harlow: Pearson

Lowe, A.T. and Collins, D.N. (2001). Modelling runoff from large glacierised basins in the Karakoram Himalaya using remote sensing of the transient snowline. *Remote Sensing and Hydrology, 267*, 99-105.

Rango, A. and Martinec, J. (1995). Revisiting the degree-day method for snowmelt computations. *Water Resources Bulletin*, *31*(4), 657-669.

Schaper, J., Martinec, J. and Seidel, K. (1999). Distributed mapping of snow and glaciers for improved runoff modelling. *Hydrological Processes, 13*, 2023-2031.

Turpin, O.C., Ferguson, R.I. and Clark, C.D. (1997). Remote sensing of snowline rise as an aid to testing and calibrating a glacier runoff model. *Physics and Chemistry of The Earth, 22*(3-4), 279-283.