Computers & Geosciences 92 (2016) 90–103

Contents lists available at ScienceDirect

Computers & Geosciences

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

Research paper

Automated modelling of spatially-distributed glacier ice thickness and volume

William H.M. James*, Jonathan L. Carrivick

School of Geography, University of Leeds, Woodhouse Lane, Leeds, West Yorkshire LS2 9JT, UK

ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form
13 April 2016
Accepted 15 April 2016
Available online 16 April 2016

Keywords:
Ice thickness distribution
Glacier volume
Subglacial topography
Glacier centrelines
Perfect-plasticity

ABSTRACT

Ice thickness distribution and volume are both key parameters for glaciological and hydrological applications. This study presents VOLTA (Volume and Topography Automation), which is a Python script tool for ArcGIS™ that requires just a digital elevation model (DEM) and glacier outline(s) to model distributed ice thickness, volume and bed topography. Ice thickness is initially estimated at points along an automatically generated centreline network based on the perfect-plasticity rheology assumption, taking into account a valley side drag component of the force balance equation. Distributed ice thickness is subsequently interpolated using a glaciologically correct algorithm. For five glaciers with independent field-measured bed topography, VOLTA modelled volumes were between 26.5% (underestimate) and 16.6% (overestimate) of that derived from field observations. Greatest differences were where an asymmetric valley cross section shape was present or where significant valley infill had occurred. Compared with other methods of modelling ice thickness and volume, key advantages of VOLTA are: a fully automated approach and a user friendly graphical user interface (GUI), GIS consistent geometry, fully automated centreline generation, inclusion of a side drag component in the force balance equation, estimation of glacier basal shear stress for each individual glacier, fully distributed ice thickness output and the ability to process multiple glaciers rapidly. VOLTA is capable of regional scale ice volume assessment, which is a key parameter for exploring glacier response to climate change. VOLTA also permits subtraction of modelled ice thickness from the input surface elevation to produce an ice-free DEM, which is a key input for reconstruction of former glaciers. VOLTA could assist with prediction of future glacier geometry changes and hence in projection of future meltwater fluxes.

1. Introduction

Knowledge of contemporary regional ice thickness distribution is poor (Farinotti et al., 2009), with field measurements impractical and data requirements making larger scale modelling studies difficult. In the context of ongoing climate change, large scale assessments are important because a climate signal extracted from an individual glacier may not be representative of the entire region (Hoelzle et al., 2007). Furthermore, it is total regional ice volume that is essential for exploring the response of glaciers to climate change (Chinn et al., 2012) and for the projection of meltwater availability (Kaser et al., 2010). Ice thickness distribution is required for glacier dynamics models (e.g. Oerlemans et al., 1998) and for assessing the impact of climate change on the hydrology of glaciated catchments (e.g. Huss et al., 2008). Glacier bed topography derived via distributed ice thickness estimations can be used to reconstruct palaeoglaciers (Benn and Hulton, 2010), and the resultant equilibrium-line altitudes are a widely-used source of palaeoclimatic information (e.g. Benn and Ballantyne, 2005). Glacier bed topography is also of great assistance in understanding glaciological hazards, such as jökulhlaups routing from or sourced subglacially (e.g. Carrivick, 2007; Staines and Carrivick, 2015), and for understanding subglacial lake formation (Frey et al., 2010). Therefore, the development of methods for assessing regional ice thickness distribution is essential for improving our understanding of many glaciological, hydrological and climatological issues.

Distributed ice thickness and ice volume can either be calculated by interpolating field measurements or by modelling. Ice thickness can be measured via boreholes (e.g. Hochstein et al., 1998) or by reflection techniques such as seismics (e.g. Shean et al., 2007) or radar (e.g Singh et al., 2012). Although impractical for regional scale studies, field measurements are crucial to parameterise (e.g. Bahr et al., 1997) and validate (e.g. Li et al., 2012) models. Due to the logistical and technical difficulties of field measurement, scaling laws are often employed to estimate glacier

---

* Corresponding author.
E-mail address: gy06whmj@leeds.ac.uk (W.H.M. James).

http://dx.doi.org/10.1016/j.cageo.2016.04.007
0098-3004/

volumes at regional scales (Bahr et al., 1997). However, scaling approaches do not account for individual glacier characteristics and do not yield information on bed topography. Furthermore, errors may be in excess of 50% for individual glaciers, reducing to 25% for regional volume (Meier et al., 2007).

A variety models to estimate ice thickness based on viscous flow mechanics and mass turnover are available (e.g. Farinotti et al., 2009; McNabb et al., 2012; Michel et al., 2013), and they have ability to estimate ice thickness with an accuracy of ~25% (Farinotti et al., 2009). However, these existing models invariably require glacier specific datasets such as mass balance (e.g. Michel et al., 2013), surface velocity fields (e.g. McNabb et al., 2012) or the manual digitisation of flowlines and ice flow catchments (Farinotti et al., 2009), limiting their use for regional scale application. A neural network approach has also been developed (Clarke et al., 2009), although it has only been tested against artificial “horizontal lake-like” glaciers and is acknowledged to be computationally intensive, limiting its effectiveness for regional studies.

An alternative approach utilises the perfect plasticity assumption (Nye, 1951), that glacier ice thickness (h) can be found from a glacier surface slope α by the relation:

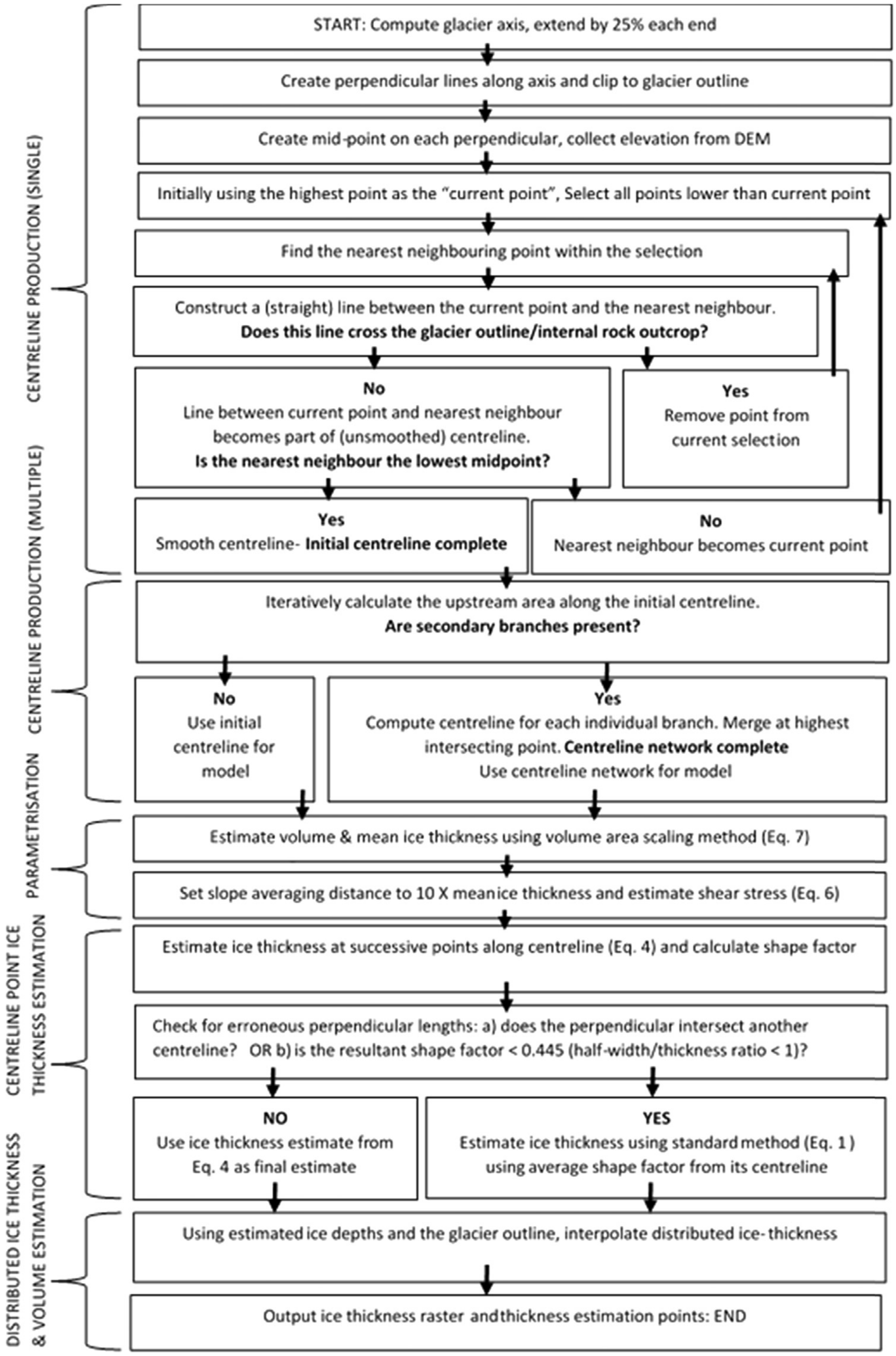

Fig. 1. Flowchart conceptually illustrating the automatic generation of glacier centrelines and estimation of distributed ice thickness and volume with VOLTA.