AN ASSESSMENT OF A TECHNIQUE TO DERIVE STREAM LONGITUDINAL PROFILES – A GIS APPROACH

Juanita Moolman

BSc(Hons) Hydrology; BSc(Hons) Geography

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Department of Geography

University of the Free State, Bloemfontein

Supervisor: Dr CH Barker

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DECLARATION

I declare that the dissertation hereby submitted for the degree Master of Science in Geography (GIS), at the University of the Free State in Bloemfontein, is my own original work and has not previously been submitted by myself at another university/faculty.

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ABSTRACT

An assessment of a technique to derive stream longitudinal profiles – a GIS approach

Keywords: contour, digital elevation model, elevation, GIS, river longitudinal profile, slope, SRTM, topographic map

The South African Water Act (Act 36 of 1998) (NWA, 1998) requires the calculation of the amount of water required for ecological sustainability in aquatic systems. Part of this process is the classification of slopes according to geomorphological class, which in turn requires, *inter alia,* the derivation of river longitudinal profiles from which to calculate these slopes. This has prompted the need to develop a method for obtaining these slopes that is fast and repeatable, and can be applied at both a national as well as sub-catchment level. Input data sets are required that are consistently available at a national as well as a sub-catchment level. This study will assess the results of using a semi-automated GIS procedure to derive longitudinal river profiles and slopes, based on nationally available data sets, in a test catchment.

In recent years the use of Digital Elevation Models (DEMs) is replacing contour lines on topographic map sheets as the source of elevation inputs required to construct longitudinal profiles. The main question put forward is: can river longitudinal profiles and slopes generated from a DEM and based on 1:500 000 mapped river lines adjusted to within 50m of 1:50 000 mapped river lines, be used as effectively as river longitudinal profiles extracted from 1:50 000 mapped contours and based on 1:50 000 mapped rivers lines?

Primary catchment X, situated in eastern South Africa, is used as the test area for this study. River channels in this catchment represent a range of slopes, from steep mountains streams to flat lowland rivers. The assessment is undertaken on 109 rivers identified at 1:500 000 scale in primary catchment X. These river lines are based on those originally scanned and vectorised from 1:500 000 topographic map sheets. These lines are available at a national level, have been connected to form a continuous network and horizontally adjusted to improve locational accuracy to within 50m of the river lines on 1:50 000 topographic map sheets (DWAF, 2003; DWAF, 2006). Profile elevation values extracted from three medium to low resolution Digital Elevation Models are examined in this study.

This study compares slopes based on the elevation values extracted from DEMs according to adjusted 1:500 000 river lines, to those extracted from contour lines on 1:50 000 topographic map sheets according to 1:50 000 scanned river lines. These input data sets and any limitations associated with them are discussed. A semi-automated method used to extract and compile the elevation and distance values required to construct longitudinal profiles and the statistical tests and procedures used to compare elevation and slope values, are also described.

Comparisons are formed around two reference scenarios. In the first elevations are extracted at the intersections of river lines with 1:50 000 scanned contour lines. The second reference scenario uses these same derived longitudinal profiles, but divided into five sets of equal horizontal intervals: 100m, 200m, 300m, 400m and 500m.

Finally, the conclusions that can be drawn form these results, together with any recommendations for either improving or even replacing the data sets and methods described in this study, are presented. It is found that, that when comparing slopes derived from 1:50 000 contour line elevations to those based on DEM elevations, steep slopes tend to be more underestimated by the DEM than flatter slopes. More than 90% of profiles based on contour intervals and more than 90% of slopes derived at 500m horizontal distance intervals show no significant difference between slopes. It is finally suggested that the adjusted 1:500 000 river lines available from DWA (DWAF, 2003; DWAF 2006) combined with elevations from medium to low resolution DEMs can be used as a substitute for 1:50 000 river line and contour line-based profiles. It is also suggested that the automated GIS procedure used to extract and combine these values can be applied in other areas where the 1:500 000 river lines and medium to low resolution DEMs are available.

OPSOMMING

'n Beoordeling van' n tegniek om stroom lengteprofiele te onttrek - 'n GIS-benadering

Sleutelwoorde: kontoer, digitale hoogtemodel, hoogtes, GIS, rivier lengteprofiel, helling, SRTM, topografiese kaart

Die Suid-Afrikaanse Nasionale Waterwet (Wet 36 van 1998) vereis die berekening van waterbehoeftes vir ekologiese volhoubaarheid in akwatiese stelsels. Hierdie sluit in die klassifikasie van rivierhellings in terme van geomorfologiese klasse, en dus ook die ontrekking van rivier lengteprofiele as basis vir die berekining van hierdie hellings. Dit is nodig om ‘n vinnige en herhaalbare metode te ontwikkel wat rivierhellings op ‘n nasionale sowel as opvanggebied skaal, kan voorsien. Data vir die metode moet dus ook op ‘n nasionale sowel as opvanggebied skaal beskikbaar wees. Hierdie studie ondersoek resulte van ‘n semi-outomatiese GIS (Geografiese Inligtingstelsel) metode om rivier lengteprofiele en hellings te ontrek, in ‘n toetsopvanggebied. Data wat gebruik word moet ook beskikbaar wees op ‘n nasionale vlak,

Die gebruik van digitale hoogtemodelle (DHM) vervang al hoe meer kontoerlyne op topografiese kaarte as ‘n bron van hoogtewaardes om lengteprofiele saam te stel. In die studie word die primere vraag: Kan lengteprofiele en hellings gebaseer op ‘n DHM en op gekarteerde rivierlyne op `n 1:500 000 skaal, en aangepas tot binne 50m van 1:50 000 gekarteerde lyne, vergelyk word met dié wat gebaseer is op 1:50 000 gekarteerde kontoerlyne en rivierlyne, ondersoek.

Die studiegebied is Primêre dreineringsbekken X in Mpumalaga (oostelike Suid-Afrika). Riviere in hierdie opvanggebied verteenwoordig ‘n verskeidenheid van hellings, vanaf steil bergstrome na die vlaktes van die Laeveld. Teen ‘n skaal van 1:500 000 behels die dreineringsbekken 109 rivierlyne, gebaseer op 1:500 000 geskandeerde en versyferde topografiese kaarte. Die lyne is nasionaal beskikbaar, vorm ‘n ongebroke lynnetwerk en is horisontaal aangepas tot binne 50m van die riviere op 1:50 000 topografiese kaarte (DWAF, 2003; DWAF, 2006). Hoogtewaardes vir vergelyking is onttrek van drie medium na lae resolusie digitale hoogtemodelle.

Helllings onttrek van die DHM volgens die aangepaste 1:500 000 rivierlyne is vergelyk met dié onttrek van kontoerlyne en riviere op 1:50 000 topografiese kaarte. Hierdie datastelle sowel as hulle beperkings is bespreek. Die semi-outomatiese metode wat hoogte en afstand waardes onttrek, sowel as die statistiese prosedures wat gebruik word om vergelykings te maak, is ook bespreek.

Vergelykings is gemaak op die basis van twee scenarios. In die eerste scenario is hoogtes vir lengteprofiele ontrek op 1:50 000 geskandeerde rivier en kontoerlynkruisings. In die tweede scenario is hierdie lengteprofiele ingedeel in vyf stelle horisontale afstande: 100m, 200m, 300m, 400m and 500m.

Laastens word die gevolgtrekkings en enige aanbevelings wat voortspruit uit die studie, bespreek. Die bevinding is dat as hellings wat gebaseer is op 1:50 000 kontoerlyne vergelyk word met dié wat gebaseer is op DHM hoogtes, is steil hellings meer onderskat deur die DHM as meer gelyk hellings. Meer as 90% van die profiele gebaseer op die afstande tussen kontoerlyne en meer as 90% van dié gebaseer op 500m horisontale afstande het geen betekenisvolle verskille tussen hellings nie. Dit is voorgestel dat lengteprofiele gebaseer op 1:50 000 rivier en kontoerlyne, vervang kan word met lengteprofiele gebaseer op die aangepaste 1:500 000 riverlyne beskikbaar vanaf DWA (DWAF, 2003; DWAF 2006) en gekombineer met hoogtes onttrek van medium na lae resolusie digitale hoogtemodelle. Dit is ook voorgestel dat die outomatiese GIS prosedure wat benut word om waardes te onttrek en kombineer ook gebruik kan word in ander dele waar 1:500 000 riverlyne en ‘n medium tot lae resolusie DHM beskikbaar is.

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CHAPTER 1
INTRODUCTION

1.1 Introduction

This study is closely tied to the responsibilities of the South African Department of Water Affairs (DWA) to provide national-scale water resource information and assessments. South Africa introduced a new National Water Act in 1998 (Act 36 of 1998) (NWA, 1998) and it is the role of DWA to develop the procedures and data sets needed to implement this new legislation. In response to this a GIS-based semi-automated method using Digital Elevation Models (DEMs) and 1:500 000 scale scanned river lines has been developed. River longitudinal profiles and associated slopes are produced which can be used as input to procedures related to national-level resource protection and management. The accuracy of the output profiles will be constrained by the availability and accuracy of the input data, particularly if considering an approach to be extended to a national scale. The focus of this thesis is the assessment of the suitability of this method in estimating longitudinal river profiles and slopes at a scale relevant to national applications, given the input constraints. The method is tested in primary catchment X situated in eastern South Africa.

1.2 Motivation

The South African National Water Act is aimed at providing sufficient water of an adequate quality and quantity to satisfy both human and ecological needs – expressed as the Basic Human Needs Reserve and the Ecological Reserve. To meet these needs goals have to be set which can enable the long term, sustainable provision of water for all South Africans, without ignoring the requirements of the environment. The Ecological Reserve can be described as the water required to protect the aquatic ecosystem to enable an ecologically sustainable use of the water resource. The determination of this Reserve for South African rivers is legislated by the South African National Water Act (Act 36 of 1998) (NWA, 1998). The National Water Resource Strategy (NWRS) produced in 2004 (DWAF, 2004), further outlines the ways in which the country's water resources should be protected, used, developed, conserved, managed and controlled to meet the requirements of the National Water Act (Act 36 of 1998).

The NWRS describes the need to set objectives for the desired condition of water resources and to put in place measures to control water use so as to limit environmental impacts to acceptable levels. This supports the introduction of Resource Directed Measures (RDM) that will focus on the overall health of the resource (including water quality and quantity, in-stream and riparian habitat conditions and an assessment of aquatic biota conditions) as a measure of its ecological status (DWAF, 1999). The Resource Directed Measures are based on a national Water Resource Classification System, which provides the framework within which management decisions can be made based on permissible and sustainable water use (DWAF, 1999). The characteristics according to which the resource is classified include chemical and physico-chemical, biological and hydro-geomorphological attributes (DWAF, 2004).

One of the first steps after the initiation of an RDM study in a catchment is the setting of historical reference conditions as a basis for comparison. To establish these, an RDM study is undertaken at riverine sites selected according to, *inter alia,* ecoregion and resource units such as geomorphological zone. Rowntree and Wadeson (1999) proposed a geomorphological classification system for South African rivers with longitudinal channel slope being one of the main inputs. This is the classification system most widely adopted in RDM studies. Given that these studies are undertaken at various catchments across South Africa, it has become necessary to develop rapid ways of deriving the necessary data inputs and making them available at a national scale.

Historically, river channel profile and slope was determined manually from the river and contour lines on 1:50 000 scale topographical paper maps. It is also the method applied originally by Rowntree and Wadeson (1999). However, this method is time consuming and labour-intensive, particularly if a large number of rivers are involved. With Geographic Information Systems (GIS) and Digital Elevation Models (DEMs) more rapid, automated, methods can be developed to extract elevations along a river, enabling large numbers of longitudinal profiles to be processed at a time.

At the time of undertaking this study there was no hydrologically correct DEM available for South Africa. Therefore, there is still a dependence on mapped river lines to represent the rivers of a catchment in any large-scale study. This study will investigate the application of available Digital Elevation Models and scanned digital river lines, to acquiring the necessary river longitudinal profiles and associated slopes. A minimum requirement for the input data sets investigated in this study is that they are available not only for the catchment on which this study is based but also at a national scale. If the study proves to be successful in the X catchment the necessary data sets will therefore be available to derive longitudinal profiles and slopes in the same manner for other catchments in the country.

Elevations from three DEM resolutions are assessed: a 20m x 20m resolution DEM; a 90m x 90m resolution DEM; and a 200m x 200m DEM. River lines initially scanned and vectorised from the 1:500 000 topographic map sheets of South Africa are used because they have been pre-processed to form a connected network of lines easy to import into any automated procedure (Silberbauer and Wildemans, 2003; DWAF, 2006) which is available for the entire country as well as including river lines in the catchments conterminous with South African catchments. Further enhancement of the 1:500 000 set of river lines includes horizontal adjustment to be within 50m of 1:50 000 scanned river lines. This is the rivers data set according to which ecological and water quality information is currently reported on by the South African Department of Water Affairs: Directorate Resource Quality Services and others (Hohls *et al*, 2002; Nel *et al*, 2004; Nel *et al*, 2006; Nel *et al*, 2009).

1.3 Problem Statement

The aim of this study is to evaluate an alternative method of obtaining the elevation and distance values required to determine river longitudinal slopes. The study will produce longitudinal river profiles for primary catchment X in eastern South Africa based on 1:500 000 scanned river lines and elevations extracted from DEMs at three resolutions.

To be able to assess the accuracy of slopes interpolated along these profiles requires that they be compared against something to be used as standard. Ideally these ought to be points that have been measured using surveying techniques. Such information is available for South Africa as spot heights maintained by the Chief Directorate of National Geospatial Information (CDNGI) of the South African Department of Rural Development and Land Reform. However, these represent high points, while rivers are situated at catchment low points. There is very limited accurately surveyed data for rivers of South Africa. Where it exists it has been undertaken for localised projects and according to project-specific requirements. The Department of Water Affairs surveys river sections upstream and downstream of gauging weirs constructed by them, but these measurements do not extend more than a matter of meters beyond the sphere of influence of the weir structure. More recently the advent of LiDAR has introduced a source of fine resolution highly accurate elevation values, but due to the cost of this technology, applications, again, are very project specific.

Given this shortage of field values against which to compare it is decided to compare the longitudinal profiles based on 1:500 000 river lines and elevations and slopes derived from DEMs, against those obtained from 1:50 000 river line based profiles as a reference. River lines from 1:50 000 scale map sheets have been scanned and vectorised for South Africa by CDNGI but are not available as a set of single connected lines forming a continuous network that can be input into GIS analyses. For the purposes of this study, therefore, a set of 1:50 000 scanned river lines in primary catchment is collated and processed to form a continuous network of lines.

With these 1:50 000 scale derived profiles as the baseline for comparison longitudinal river profiles based on the 1:50 000 scanned river lines and 1:50 000 scanned contour lines are compared to longitudinal river profiles based on elevations extracted from the

DEMs and 1:500 000 mapped river lines that have been adjusted to within 50m of the 1:50 000 map river lines (Silberbauer and Wildemans, 2003; DWAF, 2006).

The questions arising are:

- How accurate are the river longitudinal slopes calculated from available DEMs and 1:500 000 river lines, using an algorithm developed for the GIS at Department of Water Affairs and Forestry (Moolman, 2008)?
- Is there a difference in accuracy between various slope categories e.g. steep classes *vs* flatter classes?
- Are slopes collected from these apparently dissimilar sources in terms of scale and resolution a sufficiently suitable substitute for the 1:50 000 contour-derived information?
- Can it be said that medium to low resolution Digital Elevation Models and automated GIS provide an effective means of attaining river characteristics such as longitudinal channel slope for applications at a national level?
- And, therefore, is it reasonable to extend the methodology of this study to a national level?

1.4 Hypothesis

Based on this problem statement, the primary question to answer is summarized as: can river longitudinal profiles and slopes generated from a DEM and based on 1:500 000 mapped river lines adjusted to within 50m of 1:50 000 mapped river lines, be used as effectively as river longitudinal profiles extracted from 1:50 000 mapped contours and based on 1:50 000 mapped rivers lines?

In this study the main research hypothesis (H_1) proposed is that there is a significant difference between the profiles and associated slopes derived from 1:50 000 river lines and contour line intersections and those derived from DEMs and 1:500 000 adjusted river lines. The null hypothesis (H_0) for the study is that there is not a significant difference between the profiles and associated slopes derived from 1:50 000 river lines and contour line intersections and those derived from DEMs and 1:500 000 adjusted river lines.

1.5 Procedure

To answer these questions requires comparisons between the results obtained using various methods. River longitudinal profiles are based on distance along a line plotted against elevations measured at distances along this line. Once a profile has been produced slopes can be interpolated between any two points along this profile. River elevation and slope values extracted along 1:500 000 river lines overlaid on three DEMs are compared to those derived from the river line/contour intersections on 1:50 000 topographic map sheets. Digital Elevation Models at three different resolutions are used: 20m x 20m resolution, 90m x 90m resolution, and 200m x 200m resolution.

The river longitudinal profiles and associated slopes derived from the various input sources are compared to each other to assess the extent of similarity between them.

Two sets of longitudinal profiles are produced:

A. derived by overlaying 1:50 000 scanned river lines and 1:50 000 contours
B. derived by overlaying 1:500 000 river lines (digitally adjusted to within 50m of the 1:50 000 lines) with the 20m, 90m and 200m resolution DEMs

The comparisons of these profiles are divided into two main scenarios:

Scenario 1: Elevations and slopes from A and B are compared at the same horizontal points along the profiles as the 1:50 000 river line/contour intersections

Scenario 2: Elevations and slopes from A and B are interpolated and compared at regular horizontal distance intervals (100m, 200m, 300m, 400m and 500m distance intervals)

These two scenarios are chosen to represent various resolutions at which slopes can be compared to explore whether differences between A and B vary according to the resolution at which they are used. Results are analysed in terms of actual differences as well statistical significance.

The methods described in this study are based on the DEMs as released by their various sources with the underlying assumption that any error analysis undertaken at source has been sufficient to make the DEM usable for the purposes of this research. A principal idea is that the method put forward here is sufficiently robust to cater for inherent DEM error. Therefore, this study will not include a detailed error analysis of each DEM or extend to a detailed comparison of the DEMs in question. The DEMs will also not be refined any further by correcting for inherent elevation errors e.g. vegetation removal in the SRTM DEM. The removal of spurious pits in the DEMs is the only level of DEM refining that has taken place.

1.6 Study Outline

The chapters following will start by introducing Digital Elevation Models in Chapter 2. This chapter also describes some of the DEMs available for South Africa. Some of these have been produced within South Africa and are focused on applications within South African borders. Others have been produced by international organisations and cover the Southern African region, thereby also including the trans-border catchments of South African rivers. The chapter also describes both international and South African studies listed in the literature that have used DEMs to provide the elevations required to produce longitudinal river profiles.

The South African primary catchment X is chosen as the study area. The characteristics of this catchment relevant to the study are described in Chapter 3.

Elevations for the study are extracted from scanned 1:50 000 contour lines and Digital Elevation Models at three resolutions (20m, 90m and 200m). Two sources of river lines are used in the study: those scanned from 1:50 000 map sheets and those scanned from 1:500 000 map sheets and adjusted horizontally to within 50m of the 1:50 000 lines. These sources of data, and some of their limitations, are outlined in Chapter 4. This chapter then describes the methodology according to which these data sets are prepared and applied. An amount of pre-processing is required before the data sets can be compared. These steps and how they are automated is described. Next, the automated procedure used to extract elevations and calculate slopes iteratively for each main river identified in the catchment is described. Finally, the statistical tests chosen to compare profiles are described.

Chapter 5 presents the results of applying the tests listed in Chapter 4. A visual as well as a statistical comparison between profiles is undertaken. Finally, conclusions and recommendations based on these results are put forward in Chapter 6.

1.7 Study Area

Primary catchment X is situated in eastern South Africa and has an area of approximately 31 000 km^2. The catchment topography varies from very steep to very flat. It includes rivers that incorporate the range of river types found in South Africa – from steep mountain streams to flat lowland rivers, to the intermittent Nwaswitsontso and Nwanedzi rivers and their tributaries in the northern parts of the catchment. Four secondary sub-catchments exist: those of the Komati, Crocodile, Sabie and Nwanedzi Rivers and their tributaries.

1.8 Summary

This chapter has given an overview of the study described in this document. The following chapters will present the study in detail. As background Chapter 2 offers a review of Digital Elevation Models available for the South African region. It also gives a listing of studies found in the literature, which include using DEMs to derive river longitudinal slopes, both internationally and within South Africa.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The main source of elevation information for this study is the Digital Elevation Model. This chapter starts by examining what is meant by a Digital Elevation Model (a DEM). It then presents a brief review of the history of depicting surface features and the development of Digital Elevation Models. This is followed by a description of the DEMs available for the Southern African region and a description of studies that included river longitudinal slopes, both internationally and within South Africa. The emphasis is on hydrological and natural resource related studies. Finally, an overview of the issues surrounding data accuracy is presented, with the focus on the accuracy implications of using scanned/digitised river lines from maps together with the three DEMs that are used in this study. It examines the theory around deriving river physical characteristics by combining a DEM and scanned river lines, and some of the limitations/sources of error to be considered.

2.2 The Digital Elevation Model

In general terms, a Digital Elevation Model (DEM) can be described as a digital representation of the earth's surface. It is a model of the earth's surface, rather than an exact representation. This will be a more or less exact representation depending on the source of the elevation data and the procedure used to interpolate between elevation values. Errors inherent in either of these factors will affect the accuracy of the final DEM. Whether these errors are of an acceptable magnitude or not, depends on the purpose for which the DEM will be used.

A number of authors have included their definitions of a DEM:

- Lynch (2002, pg 219): " A digital elevation model (DEM) is a framework for recording spot elevations in a rectangular grid."
- Macleary and Hassan (2008, pg 324): "A digital elevation model is a grid with elevations that represent the earth's surface."
- Bi *et al* (2006, pg 54): "The digital elevation model (DEM), an important source of information, is usually used to express a topographic surface in three dimensions and to imitate essential natural geography"
- Paz *et al* (2008, pg2) refer to inconsistencies in the use of the term DEM, and define it themselves as: 'a regular gridded matrix representation of the continuous variation of relief over space'

2.3 Historical Background (from paper to computer)

Finding ways to accurately represent the earth's surface is not a new quest. In the first half of the previous century Preston E. James (1937) wrote an article entitled "On the Treatment of Surface Features in Regional Studies" in which he commented on the poor way in which he felt physical features of the landscape were being depicted. He illustrated how this poor depiction led to the poor analysis of features. He commented on the contour map being insufficient on its own to adequately represented features, particularly given the course resolution (scale) of contour maps available in the USA at that time. In the mid-1940s Robinson (1946) took this criticism further by referring to the lack of advance in surface representation since the contour in the 1800s and the paucity of studies combining both elevation and slope as descriptors.

According to Peucker (1979) engineers started using Digital Elevation Models as early as the 1950s, but it wasn't until the 1970s that applications combining elevation and location moved out of the realms of engineering and photogrammetry. Despite rapid advances in the field, progress in the storage and manipulation of spatial data post 1970 still occurred within the constraints of the technology available. As Peucker (1979) points out much of the discussion about DEMs at that time still focussed around effective data structures, although the potential of these data sets for practical applications was obvious. In the United States central agencies such as the USGS started to identify the advantages of storing their data digitally, establishing a Digital Applications Team in 1977 with the goal of producing spatial data from the National Mapping Program (McEwen and Jacknow, 1979) and archiving it in a centralized database. Along with the vector cartographic data, their data also comprised elevations in a raster (DEM) form. But systems were unable as yet to cope with the volume and complexity of relating individual spatial elements and therefore, at that stage, the USGS maintained a database of files, not of the coordinates and attributes inside the files.

Some of the limitations of spatial data sets were also apparent. Input vector data such as contours was often very generalized and at a coarse interval, affecting the accuracy of derived elevations (McEwen and Jacknow, 1979). Inconsistencies between raster elevations and the measured location of features such as streams became evident, and McEwen and Jacknow (1979) make reference to a DEM edited to match streams, roads and coastlines (McEwen and Jacknow, 1979). As far back as 1979 Peucker expressed concern about data accuracy in relation to resolution. These are issues that have remained relevant, with the resolution and accuracy of input data sets remaining one of the major sources of uncertainty in DEM derivation.

The technology of the late 1970s also played a substantial role in the extent to which the new DEMs were used in applications. The volume of data requiring storage and the processing power necessary to manipulate the data was constrained by the computer technology, and effectively restricted the resolution of data sets as well as the geographical extent and complexity of applications (McEwen and Jacknow, 1979).

Visualisation of 3D elevation data was also still limited by the ability of pen plotters, although some very creative solutions were found with an early application of hillshading using an automated plotting method described by Brassel (1974) and Brassel *et al* (1974). They derived a 100m x 100m resolution Digital Elevation Model from 1:25 000 maps using it as background shading for topographic sheets, thereby improving the portrayal of features by the automatic combination of shading and land use. The visual advantages of combining elevation and other characteristics through plotting were still being explored in 1986 when Eyton overlaid elevation with land use, land cover and temperature individually on a DEM by applying a combination of plotting to produce color negatives and photography to combine these into a map (Eyton, 1986). In South Africa Dent *et al* (1989) produced a national DEM and used a system of plotting numbers to represent altitude classes. An extract of this DEM and the numerical classes used is shown in Figure 2.1.

However, it is to our advantage today that these pioneers were so thorough in their investigations since many of the data structures and algorithms for DEM data manipulation explored then are still in use today and form the backbones of current analyses. Many of the methods currently used were developed back in the 1970s and 1980s e.g. Douglas-Peucker (1973) algorithm for line smoothing; and the D8 method of Jenson and Domingue (1988) to derive flow directions and thereby places of flow accumulation. Fairfield and Leymarie (1991) proposed a method to deal with parallel drainage lines generated in flat areas, which is still recommended in Paz *et al* (2008), and the ANUDEM algorithm first described by Hutchinson (1989; 1996) is widely applied as one of the main elevation interpolation methods for generating Digital Elevation Models from altitude points and/or contours.

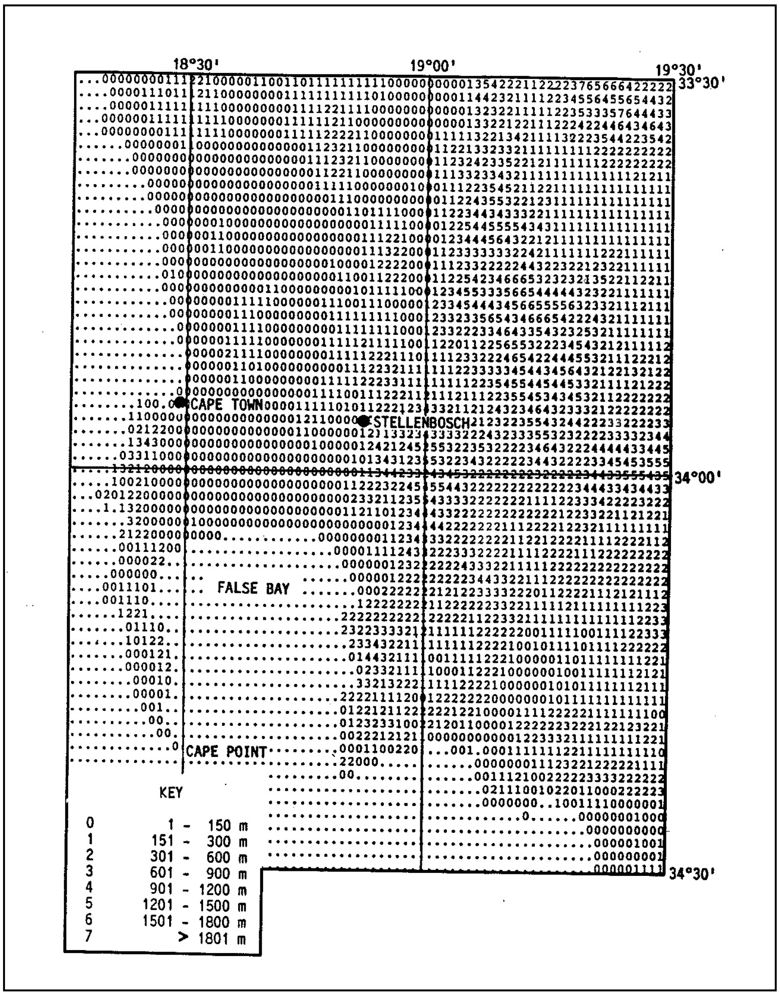


Figure 2.1: An extract of the DEM of South Africa as plotted by Dent *et al* (1989)

2.4 Digital Elevation Models relevant to South Africa

This section describes some of the Digital Elevation Models available for South Africa. The locally produced DEMs may include Lesotho and parts of Swaziland, depending on the source data extent, however, the internationally generated DEMs include countries neighbouring South Africa, making them a useful consideration for regional scale catchment analyses incorporating the main Southern African river basins extending beyond the borders of the country.

2.4.1 International

In 1988 NOAA (NOAA, 1988) released the ETOPO5 DEM at a worldwide level. The base resolution of the DEM is 5 minutes (approximately 10km) in parts of the Northern Hemisphere and Australia), but diminishes to 1 degree in much of the Southern Hemisphere, including Africa. This DEM has since been upgraded twice, first to ETOPO2 at a two minute grid, and then most recently to ETOPO1 released in 2008 with a 1 minute arc grid (Amante and Eakins, 2009).

Hutchinson (1996) describes the inputs and procedures used to generate a continent-wide DEM for Africa at a 0.05 degree resolution (3 minutes, which is approximately 5km). The elevation model is based on inputs digitised from 1:1 000 000 scale aeronautical maps of Africa. These included spot heights, contour corners at the resolution of a one minute grid, stream lines and coastlines. These datasets are combined to produce a Digital Elevation Model, using the ANUDEM algorithm derived by Hutchinson (1989).

At a resolution of 30 arc seconds (a world-wide average resolution of approximately 1km), GTOPO30 DEM is one of the first DEMs to be produced at a higher resolution (GTOPO30, 1996). It represents a resolution of approximately 800m pixel resolution in South Africa (Lynch, 2002). The DEM was produced by U.S. Geological Survey's (USGS) EROS Data Center. This DEM is based on assimilating data collected from various sources representing existing terrain models and topographic information from various parts of the world (GTOPO30, 1993). The main source of data is the Digital Terrain Elevation Dataset (DTED) derived at a three arc second resolution (approximately 100m x 100m) by the United States National Imagery and Mapping Agency (formerly the Defence Mapping Agency), and originally intended for military use. Alternative data sources are used to fill gaps in the DTED data (GTOPO30, 1996). This DTED dataset is also available publicly at a resolution of 30 arc seconds and is commonly referred to as DTED® Level 0 (NGA, 2008).

The Shuttle Radar Topography Mission (SRTM) is a joint project undertaken by NASA, the United States National Geospatial-Intelligence Agency, and the German and Italian Space Agencies. The aim was to collect a high resolution, worldwide Digital Elevation Model using radar interferometry. Data was collected during the February 2000 mission of the Space Shuttle Endeavour with the aim of producing a digital elevation model of the all land surfaces between latitudes 60° north and 56° south. (Farr *et al*, 2007). The original data was processed at a sample size of 1 arc-second (approximately 30m x 30m) resolution, but was initially only released in the USA at this resolution. Worldwide, this data was further processed and made freely available via the Internet at a 3 arc-second resolution (approximately 90m x 90m), with the 1 arc-second DEM becoming available for countries outside the USA after 2009.

In 2009 NASA and the Japanese Ministry of Economy, Trade and Industry released the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) Global Digital Elevation Model (GDEM). The ASTER GDEM is available at a global scale in tiles of 1° x 1°, in GeoTIFF format with elevation readings posted at every 30m (ASTER GDEM, 2009). ASTER is an imaging instrument operating on the NASA Terra Platform. It captures stereo image coverage of the globe, from which the GDEM can be produced by stereo-correlation. According to the validation information published together with the GDEM files, the vertical accuracy of the GDEM is between

10m and 25m RMSE (Root Mean Square Error). Breytenbach (2010) undertook a quality assessment of the ASTER GDEM for South Africa. He concluded that the GDEM could be used confidently at meso-, regional- and national scales, but that users should be aware of inherent anomalies and artefacts within the datasets.

The availability of the 1 second (approx 30m resolution in South Africa) STRM DEM and the 30m ASTER GDEM in 2009 has greatly increased the extent of medium resolution digital elevation information for Southern Africa. Weepener *et al* (2010) have subsequently produced a combined, gap-filled, DEM for Southern Africa, which includes the parts of drainage basins outside the South African borders. The SRTM DEM is used as the dominant DEM with gaps in this DEM being filled using the 1:50 000 20m interval contours to interpolate elevations in missing areas within the borders of South Africa, and the ASTER DEM being used to fill gaps in areas outside the borders.

2.4.2 National

One of the first Digital Elevation Models of South Africa was derived at the University of Natal in the 1980's (Dent *et al*, 1989; Lynch, 2002). It was based on altitude data collected from 1:50 000 topographical maps. The altitude values were manually interpolated from paper maps at the intersection points of a one minute by one minute grid over South Africa and used to produce a national DEM at a resolution of one arc minute (approximately 1600m x 1600m). The next national level DEM to be produced for South Africa was generated by the Chief Directorate Surveys and Mapping of the South African Department of Land Affairs: Chief Directorate Surveys and Mapping (DLA:CDSM) and released in 1990. (Lynch, 2002). This DEM has a resolution of 200m x 200m in the urban and more mountainous areas and 400m x 400m in the remainder of the country. It is based on a grid of point elevations derived photogrammetrically from 1:50 000 orthophotos. The former DLA:CDSM, renamed to the Department of Rural Development and Land Reform: Chief Directorate National Geo-spatial Information (CDNGI) in 2009, has recently produced a 25m x 25m DEM for South Africa (Vorster and Duesimi, 2010). This DEM is based on the earlier 400m/200m resolution DEM and a 50m x 50m resolution DEM derived by the same Department.

At a commercial level the company Computamaps, based in Cape Town, South Africa, provides a 20m x 20m resolution Digital Elevation Model of the country. This DEM is based on 1:50 000 scale digitised 20m interval contours of South Africa which can be obtained from CDNGI.

2.5 Applications

As computing ability has expanded and the potential of spatial analysis has become not only more accessible but also more evident, so the applications of digitally-derived elevations has increased. GIS and Digital Elevation models have become widely used to derive catchment morphological characteristics, relevant to hydrology, geomorphology and ecology. In hydrology DEMs are a means to simulate the physical environment through which water flows and can be used to extract values required as inputs to hydrological models (Moore *et al*, 1991; Zhang and Montgomery, 1994; Garbrecht and Martz, 1999).

Although frequently used to derive hillslope as a terrain derivative (Zhang and Montgomery, 1994; Jenson, 1991; Hutchinson and Dowling, 1991; Quinn *et al*, 1991; Gallant and Hutchinson, 1996; Giles, 1998; Walker and Willgoose, 1999; Kienzle, 2004; McMaster, 2002; Bi *et al*, 2006; Oksanen and Sarjakoski, 2006; Arrell *et al*, 2007) DEMs have also become a frequent source of longitudinal river channel slope as a geomorphological or hydrological parameter (O'Brein, 1999; Zah *et al*, 2000; Stein *et al*, 2002; Clarke and Burnett, 2003; Finlayson and Montgomery, 2003; Heitmuller, 2005; Davies *et al*, 2007; Paz and Collischonn, 2007, Neeson, 2008).

2.5.1 International

Most studies have focused on using DEMs at 30m or higher resolution at a small catchment or channel reach scale. Clarke and Burnett (2003) are of the opinion that a 30m resolution is already too low to achieve good channel slope estimates. They compared slopes extracted from a 30m x 30m DEM and those extracted from a 10m x 10m DEM against features on 1:24 000-scale topographic map sheets in thirteen test quadrangles (all less than 15km x 15km), and concluded that the 10m DEM better represented both the high and low slope classes. Neeson *et al* (2008) used 30m and 10m grid size DEMs to derive channel reach lengths in a set of catchments in Ohio and Idaho, USA, all with a reach catchment area of less than 5km^2. They found that the performance of the two DEMs in estimating reach slope varied depending on the source of digitized streams against which they are compared. They also found that the correlation between their field-measured slopes and their

Miller *et al* (1999) compared watershed and channel slope derived from five DEM resolutions ranging from 40m to 2.5m in the Walnut Gulch Experimental Watershed in Arizona. They concluded that, although the advantages the 2.5m DEM are highest at small watershed and hillslope scale, the smoothing of features associated with lower resolution DEMs is such that they remain useful at broader level scales.

However, very few studies have considered the use of low resolution DEMs at countrywide scale, in particular resolutions such as the 90m x 90m (3 arc second) SRTM DEM or lower. Stein *et al* (2002) used a 9 arc second (approx 200m) resolution

DEM of Australia to extract channel slope at reach scale for the entire continent. Paz *et al* (2007a, 2007b) applied the 90m x 90m resolution SRTM DEM to the Uruguay River catchment in South America to investigate using it to derive inputs for large basin grid-based distributed hydrological models, commonly based on resolutions lower than 90m. They re-sampled the 1 arc second, 90m x 90m SRTM DEM to 2 arc second and 5 arc second resolutions and extracted river length and reach slope using each DEM. They were unable to assess the derived slopes, but found that for river lengths the 90m x 90m DEM produced the lowest relative errors when compared to rivers digitized from LANDSAT ETM+ satellite imagery (30m x 30m resolution in the visible spectrum).

Finlayson and Montgomery (2003) derived channel slope as an input to stream power calculations in the Olympic Mountain Range of Washington State (USA) with the intent of applying similar procedures to continental scale mountain ranges such as the Himalaya where only DEMs of a large resolution are available. They were particularly interested in examining the issues of scale and resolution that become significant when extracting data from low resolution DEMs to be used at large scales. They used the 10m and 30m USGS DEMs available in the USA, but also re-sampled the 30m USGS DEM to create 90m and 900m DEMs to represent the resolutions that would be available for the Himalaya. They found a 65% decrease in the average river slope between the 30m and 900m DEM-derived river slopes and a 30%-40% decrease in average slope between the 30m and 90m DEM-derived slope and concluded that these differences need to be taken into account when assessing modelled outputs based on inputs derived at various DEM resolutions.

Other studies applied at broad scales include those of O'Brein (1999) in New Zealand and Davies *et al* (2007) in USA, but were based on DEM resolutions of 30m and higher. O'Brien (1999) used a 30m DEM derived from 20m contours to extract a river network and watersheds, and then from these computed variables such as average stream elevation and slope between stream confluences, flow source areas and stream length, as inputs to a set of classification rules to be applied at national scale in New Zealand. Davies *et al* (2007) used a 10m x 10m DEM from the USGS to derive streams and reach channel slope as input to salmon habitat assessment in the large catchment area draining into Puget Sound near Washington DC. They found a high correlation (r^2 = 0.88) between measured and DEM-derived channel gradients, with the derived slopes generally being higher than the measured slopes. Cetin and Lee (2006) recognized the value of the wide coverage of the SRTM DEM data set and undertook a study to compare watershed and river characteristics such as reach slope obtained from the 30m (1 arc second) SRTM DEM to those derived from the 10m and 30m resolution USGS (United States Geological Survey) DEMs. They found that parameters derived from the 30m DEM compared better to those derived from the 10m USGS DEM than did the same parameters derived from the 30m USGS DEM.

2.5.2 National

In terms of South Africa, very little has been published concerning the use of Digital Elevation Models to derive river longitudinal slopes. Dollar *et al* (2006) used longitudinal channel slopes of the Crocodile, Olifants, Mhlathuze and Seekoei Rivers, derived from a 20m x 20m DEM, to test a statistical method for identifying macro reach break points in slope along a river. Partridge *et al* (2010) also applied statistical methods of identifying break points in the 20m x 20m DEM-generated longitudinal slopes to delineate geomorphic provinces for South Africa. Roux *et al* (2008) used the 90m SRTM DEM to identify geomorphological zone classes in the rivers of the Kruger National Park.

Pretorius *et al* (2005) generated a 50m DEM of the Modder River catchment from 1:50 000 topographic map sheet contours. They extracted catchment areas and average river slopes at a catchment level as inputs to a database designed to store hydrological modelling inputs. Barker (2011) derived a detailed Digital Terrain Model (DTM) for the Modder River catchment. He incorporated inputs from digital topographic information and SRTM elevations to illustrate a method of generating a reliable DTM based on readily available input data sets.

However, historically, river slope inputs in South Africa are generally derived on a project-specific basis, and are mostly derived at a detailed level based on physical measurements (e.g. Grenfell *et al*, 2009, who used GPS to measure the water surface longitudinal profile of the Mfolozi River in eastern South Africa) or contours (Rowntree and Dollar, 1996; Rowntree and Wadeson, 1999; Birkhead *et al*, 2000). Rowntree and Dollar (1996) examined channel changes along a 17km stretch of the Bell River in the South African Eastern Cape region, for which they extracted channel longitudinal profiles from 1:50 000 topographic map sheets. Birkhead *et al* (2000) also measured river slopes from 1:50 000 map sheets to examine geomorphological change in the Sabie River.

Moolman *et al* (2002) derived river slopes in the Olifants, Crocodile and Sabie River catchments using a 200m DEM to obtain the elevation data required. Rowntree and Wadeson (1999) published a detailed geomorphological classification system to be applied to South African rivers, incorporating longitudinal slope measurements from topographic map sheets. This classification methodology is widely applied to projects undertaken to determine Ecological Reserves in South African rivers (Dallas, 2000a; Dallas, 2000b; Kleynhans *et al*, 2005).

2.6 Summary

This chapter has provided a contextual background to Digital Elevation Models examining some of the definitions of a DEM and how the derivation of elevation data has been considered in the last century. It also listed some of the DEMs available for South Africa as well as a number of projects undertaken which applied longitudinal river profiles using elevation data from Digital Elevation Models. The next chapter will describe the catchment used as a study area for this project.

CHAPTER 3
Description of the study area

3.1 Introduction

There are twenty-two primary catchments in South Africa. They are labeled alphabetically from A to X (excluding I and O). The X catchment is situated in Mpumalanga in eastern South Africa, shown in grey in Figure 3.1. It comprises the Komati River catchment, the Crocodile River catchment, the Sabie River catchment and the Nwaswitsontso and Nwanedzi rivers together with their tributaries.

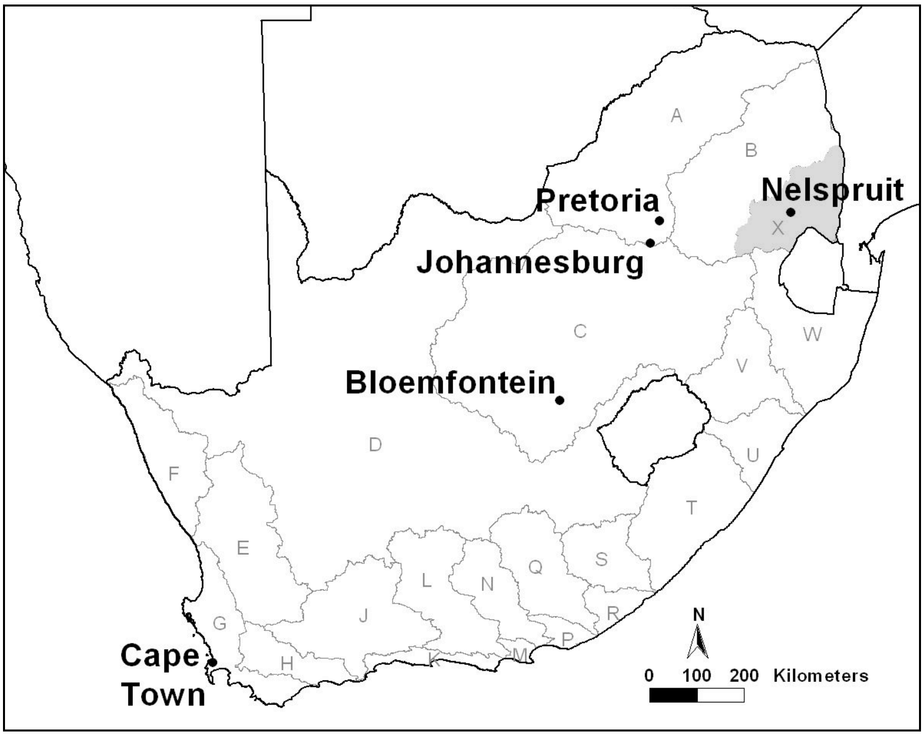


Figure 3.1: Primary catchments of South Africa (Midgley *et al*, 1994)

The blue river lines scanned from the 1:500 000 map sheets available from CDNGI represent 143 of the rivers in the catchment. The rivers rise in the Drakensberg Mountains which form the western edge of the study area and flow eastwards through the foothills into the flat Lowveld area and through the Lebombo Mountains to Mozambique (Figure 3.2). Slope classes of the scanned river lines range from steep to relatively flat, and line lengths from as short as the Dawsons Spruit (1km) to the Crocodile River, which is measured as approximately 330km long when it joins the Komati River just before it flows out of South Africa to Mozambique near Komatipoort. The range in slope and length represented in this catchment forms the basis for the choice of this catchment as the study area.

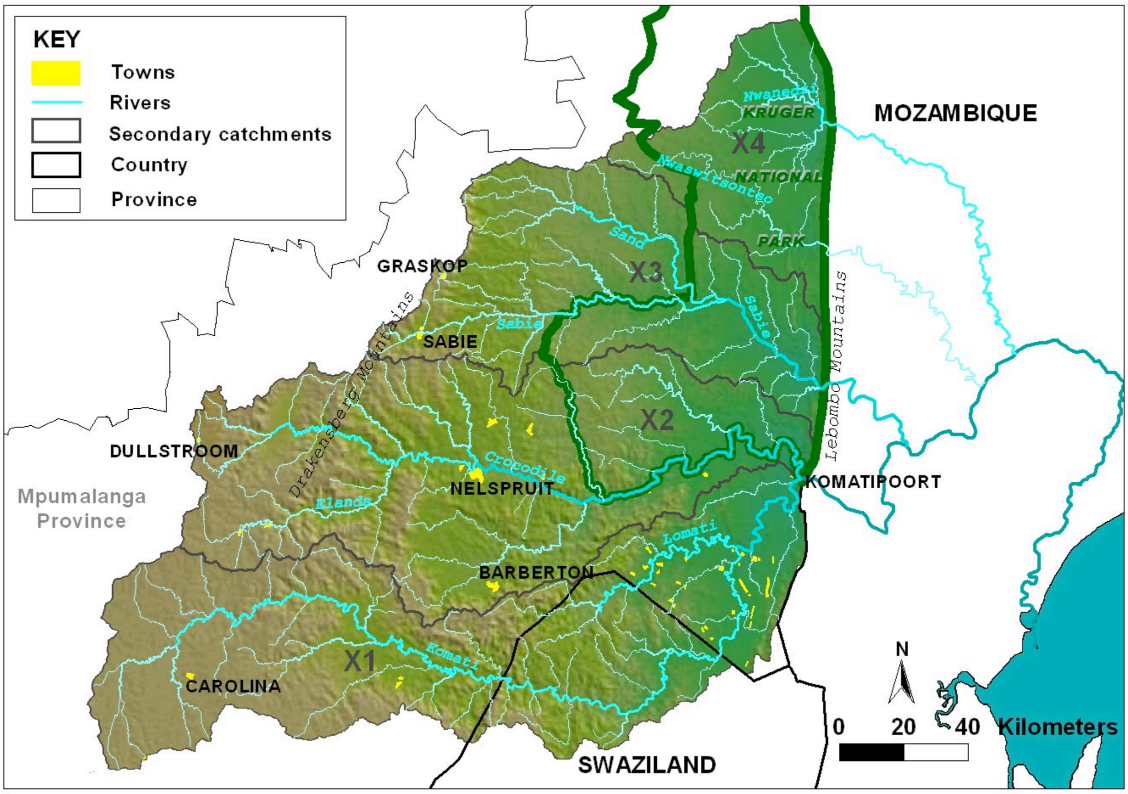


Figure 3.2: Location of the X catchment, showing main rivers and towns (CDNGI, 2006)

3.2 Catchment characteristics

Figure 3.2 shows the relative location of the study area and the main physical features of the catchments. According to the South African catchment labeling system the study area is labeled the X primary catchment region. It is made up of four secondary catchments: with X1 being the Komati River catchment, X2 the Crocodile River catchment area, X3 the Sabie River catchment and X4 comprising the Nwaswitsontso and Nwanedzi main rivers.

The main town in the area is Nelspruit, located on the Crocodile River. The catchment is part of the Department of Water Affairs Inkomati Water Management Area. It has a total area of approximately 31 000 km^2, with both plantation forestry and conservation represented as being major activities in the catchment (Figure 3.3). Approximately 7 500km^2 (24%) of the study area is situated within the Kruger National Park. The estimated required ecological reserve for the Inkomati Water Management Area (1 008 x 10^6 m^3/a) is about one third of the natural mean annual runoff (3 539 x 10^6 m^3/a) (DWAF, 2004).

Elevations range from nearly 2 300m amsl to as low as 120m amsl (Figure 3.4), with the Crocodile River having its source at over 2 000m. The Sabie River rises at more than 1 900m amsl and is at 140m amsl when it flows through the Lebombo Mountains to Mozambique.

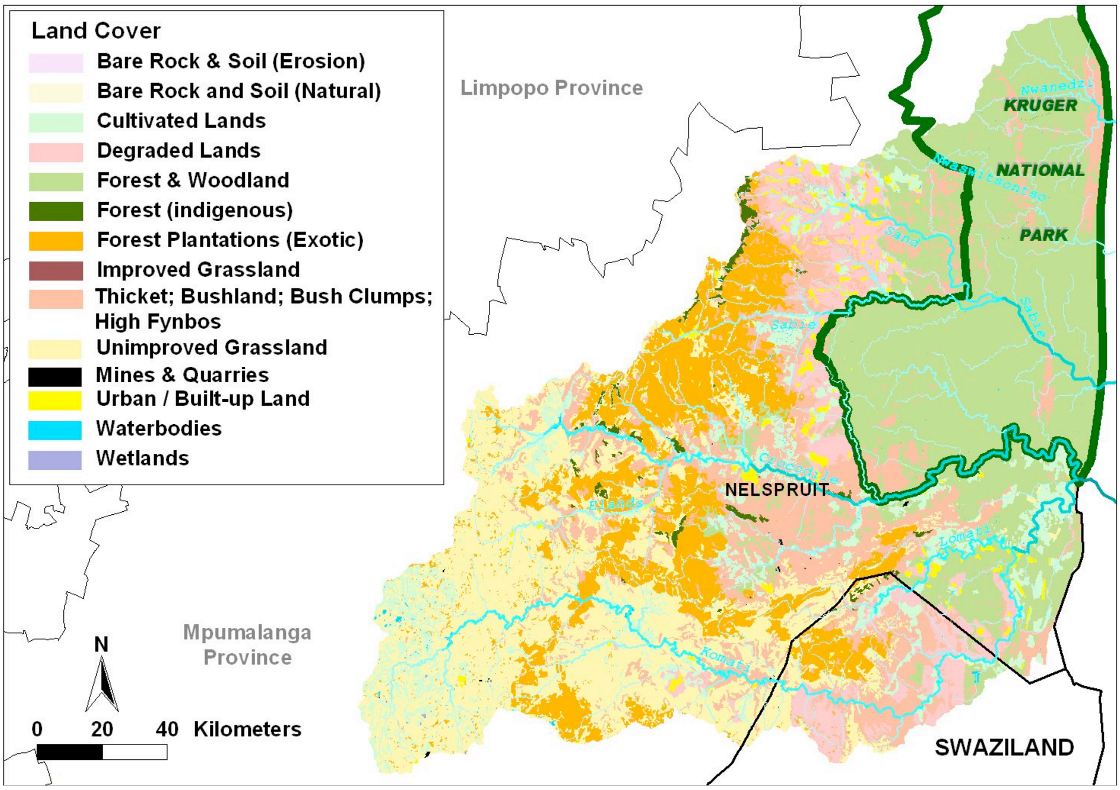


Figure 3.3: Main land cover classes in the X catchment (Thompson, 1999)

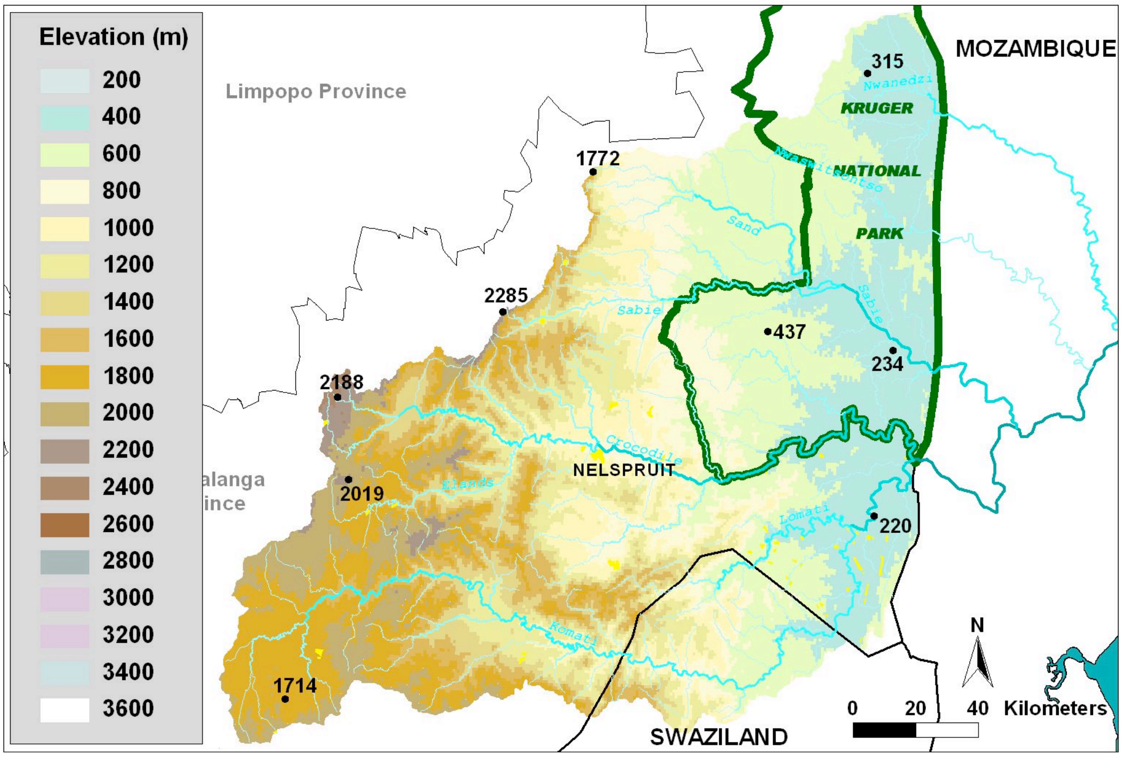


Figure 3.4: Elevations in the X catchment - spot heights and contour elevations (CDNGI, 2006)

Catchment terrain slope varies from steep in the western parts of the catchment to relatively flat in the central and eastern parts, with the exception of the Lebombo Mountains in the far eastern parts of the catchment. Twenty-eight percent of the catchment has a terrain slope above 10% and 6% of the catchment has a terrain slope below 1% (Figure 3.5).

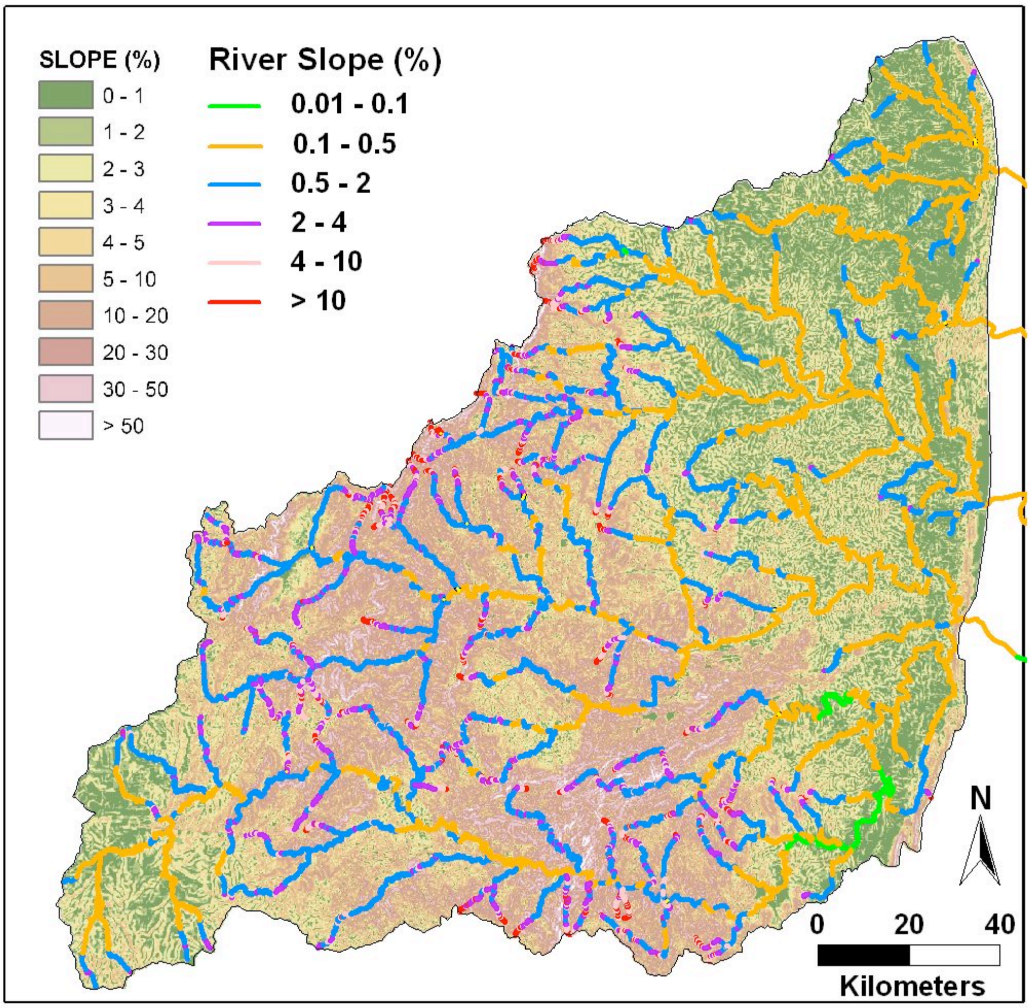


Figure 3.5: Catchment and river slope in the study area

3.3 River characteristics

The slopes of the river channels also vary from steep to relatively flat (Figure 3.5). The majority of major rivers originate in the steeper western parts of the catchment, associated with the Northern Escarpment Mountains. Two percent of the total river length represented by the 1:500 000 scanned river lines has a slope steeper than 10% and 53% has a slope of less than 0.5%. Table 3.1 shows the total length of river lines representing six slope classes in the catchment. Slope values are based on elevations extracted from the 3 arc-second SRTM DEM. The total scanned river line length is 6 712km.

Table 3.1: Percent of scanned river line length per slope class

Slope class (%)	River line length (km)	% of total line length
< 0.1	692.4	10.3
0.1 – 0.5	2 881	42.8
0.5 – 2	2 285.4	34
2 – 4	492.2	7.3
4 – 10	244	3.6
> 10	117	1.7

3.4 Summary

At a scale of 1:500 000, 143 river lines are delineated in primary catchment X. They include all the major rivers in the catchment and their tributaries: Komati River, Crocodile River, Sabie River and Nwanedzi River. River longitudinal slope classes ranging from less than 0.1% to more than 10% are represented. Chapter 4 presents the various data sources that can be used to derive elevations and slopes along river longitudinal profiles, and describes ways of comparing these derived values to each other.

CHAPTER 4
DATA SOURCES AND METHODOLOGY

4.1 Introduction

This chapter is aimed at providing background to the data sets and analysis methods used in this study. It is divided into two sections. The first describes the data sets and any existing limitations to them. The second section present the methods according to which these data sets are combined to undertake the final analysis presented in Chapter 6.

4.2 Data sources

A number of data sets are required to compare the various slope-measuring methodologies. Elevation data along the length of a river can be derived from contours, from Digital Elevation Models (DEMs), or from actual field measurements from GPS and surveying for engineering purposes. The main criteria in choosing which to use is based on scale, reliability and ease of availability. This section provides a detailed description of the data sources used for this study, as well as some of the issues surrounding their accuracy and the limitations that need to be considered when using these data sets.

4.2.1 Digital Elevation Models

The DEM that is used must be available for the entire country, including the catchments in neighbouring countries contiguous with South African catchments, so that ultimately measurements can be made for any stream in any catchment impacting on (or from) South Africa. As of 2009 three DEMs are most commonly used at DWA (listed in Table 4.1): a 20m resolution DEM, a 90m resolution DEM and a combined 200m/400m resolution DEM.

DEM20

In 2002 DWAF purchased a 20m x 20m DEM for South Africa, which was derived for commercial purposes by the private company ComputaMaps (2002). The DEM was based on spot heights, 20m contours, coastlines and inland water surface areas captured automatically from the 1:50 000 map sheet series. CDNGI generates 1:50 000 map sheets photogrammetrically from 1:30 000 aerial photographs, and the data is available digitally. ComputaMaps used the ANUDEM algorithm (Hutchinson, 1989) to interpolate between the digital 1:50 000 contours, and 1:50 000 river lines and water surface areas were used to force drainage lines. To facilitate ease of use this DEM will be referred to as DEM20 for this study. Both DWAF (2006) and Barker (2011) point out that contour-derived DEMs are subject to errors of interpolation, especially in flat areas, which can affect the accuracy of elevation values extracted from them.

According to the DWAF (1997) report on spatial data standards the accuracy standard applied requires that 95% of points that can be tested by must be within 37.5m of its true position on the ground. Error measurement in the 20m x20m DEM was undertaken by evaluating Root Mean Square Errors (RMSE). According to the metadata released together with the DEM the planimetric RMSE is 15.24m and the total vertical RMSE is 6.8m (based on 90% error measurements).

DEM90

The Shuttle Radar Topography Mission (SRTM) was a joint project undertaken by NASA, the United States National Geospatial-Intelligence Agency (NGA), and the German and Italian Space Agencies. The aim was to collect a high resolution, worldwide Digital Elevation Model using radar interferometry. To achieve this goal, elevation data was collected by radar during the February 2000 mission of the Space Shuttle Endeavour and used to produce a digital elevation model of the all land surfaces between latitudes 60° north and 56° south. (Farr *et al*, 2007)

The original data was processed at a sample size of 1 arc-second (approximately 30m x 30m) resolution. This data has been further processed and made freely available via the internet at a 3 arc-second resolution (approximately 90m x 90m in the South African region) It can be downloaded from the United States Geological Survey (USGS) website (JPL, 2009). Rodriguez *et al* (2006) describe the error assessment procedures undertaken on the SRTM data. Overall results are presented per continent and based on absolute differences between the SRTM radar-derived elevations and actual GPS-derived elevations, with 90% accuracy. The original specifications for the collection of the SRTM DEM identified 16m as the required absolute vertical error for the elevation values. However, Rodriguez *et al* (2006) calculated an absolute geo-location error of 11.9m and an absolute vertical error of 5.6m for Africa.

Some points to note are that measurements do not penetrate vegetation or water, and, despite the broad coverage of the data, there are still gaps present in the DEM, particularly in very steep or very flat areas or where water or shadow prevented the measurement (Farr *et al*, 2007). The CGIAR-CSI (Consultative Group on International Agricultural Research - Consortium for Spatial Information) has made available a post-processed version of the SRTM 90m x 90m DEM (Jarvis *et al*, 2008). The gaps have been filled by including data from supplementary DEMs and a range of interpolation algorithms (Reuter *et al*, 2007). The coastline has been clipped to include estuaries (Jarvis *et al*, 2008) according to the Shorelines and Water Bodies Database (SWDB) which is also available for download together with the original SRTM DEM. This data can be downloaded from the CGIAR-CSI website (Jarvis, 2008). This is the version of the SRTM DEM that is used in this study and referred to as DEM90.

DEM200

The Chief Directorate National Geo-spatial Information (CDNGI) has produced a DEM for South Africa with a resolution of 200m in the urban and more mountainous areas and 400m for the remainder of the country. It is based on a grid of point elevations derived photogrammetrically from orthophotos. According to the CDNGI these points have an absolute height accuracy of ±10m. These points were used at DWA to produce a re-sampled DEM at 200m x 200m resolution based on the ANUDEM (Hutchinson, 1989) algorithm. This DEM will be referred to as DEM200 for this study.

Not all the DEM sources described here have published the absolute errors inherent in their model. Published error values are based on either RMSE or absolute error. According to Zukowskyi *et al* (2000) Root Mean Square Error (RMSE) is often used to describe the errors associated with a Digital Elevation Model. However, they point out that this is a measure of relative error only and cannot be considered to represent absolute errors. Only if the reference data used to calculate the RMSE is different to the original source of the DEM can the RMSE be considered to reflect absolute error, as it will also account for any random or systematic error produced in the DEM. If the input dataset to the DEM and the reference dataset used to calculate the RMSE are the same, systematic and random errors remain consistent in both data sources and will not be reflected in the RMSE. In determining their errors both DEM20 and DEM200 were compared to the same data set as used in their generation (contours and/or spot heights). DEM90 elevations values, however, were compared to GPS-derived elevations and can be assumed to have a more relevant assessment of error.

Of the three DEMs discussed above, only DEM90 includes catchment areas in neighbouring countries. Table 4.1 summarises the characteristics of the DEMs used in this study. Figure 4.1 shows a sample area of the three DEMs, illustrating the differences in pixel size at each resolution. Pixel size affects the dimensions of features which can be resolved from a DEM. This becomes important in this study where steep features such as water falls or dam walls occur in the river longitudinal profile (Moolman *et al,* 2002).

Table 4.1: A summary of Digital Elevation Model characteristics

	DEM20	DEM90	DEM200
Resolution	20m	90m	200m / 400m
Extent	RSA, Swaziland, Lesotho	RSA, Swaziland, Lesotho, Namibia, Botswana, Zimbabwe, Mozambique	RSA
Source	Contours	Radar	Points
Access	Cost	Free	Free

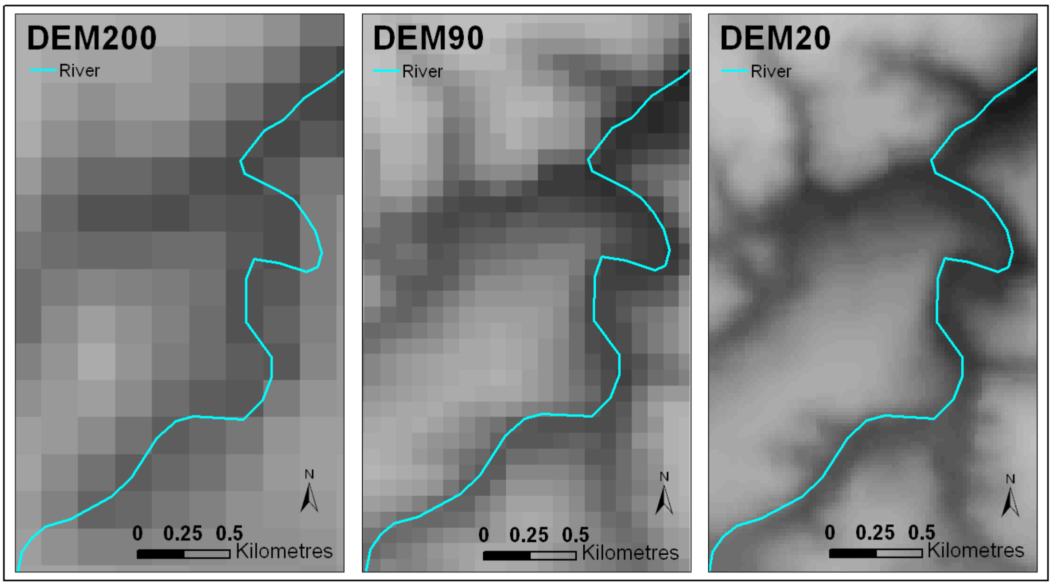


Figure 4.1: Comparison of a section of DEM200, DEM90 and DEM20

4.2.2 Rivers

4.2.2.1 Sources

Two available sets of digital river lines are relevant to this study:

- River lines that have been scanned and vectorised from the blue plates of **1:50 000** map sheets.

  These vector lines are available from CDNGI per 1:50 000 topographic map sheet (1 924 sheets in all). They have not been combined into a national coverage; nor have any of the issues mentioned below in section 4.2.2.2 been addressed, except where required for specific studies such as the one discussed in this thesis (see also Barker, 2011). A major project has been initiated at DWA to address the network and attribute issues in the 1:50 000 scanned river lines, but is still a way from completion (Twyman, 2011). However, the 'unconnected' vectorised 1:50 000 river lines provide a useful reference data set (DWAF, 2006) and are used as the reference data set in this study.
- River lines that have been scanned and vectorised from the blue plates of **1:500 000** map sheets.

  These lines have been combined into a national coverage (24 sheets in all) and all the issues mentioned below in section 4.2.2.2 have been addressed

(Silberbauer and Wildemans, 2003; DWAF, 2006). This data set has been extended further to also provide river lines for tributaries of South African rivers in catchments in neighbouring countries. The specific details of how these issues were originally addressed in the 1:500 000 river line data set is described in section 4.2.2.3. It provides a connected network of river lines, based on the simple principle that water flows downhill in single channels (DWAF, 2006), that can be applied to studies ranging from Southern African regional scale to sub-primary catchment scale.

4.2.2.2 Issues

A number of issues exist with the identification of rivers and river networks based on digital river lines scanned from topographic map sheets. These issues are pertinent to this study in that they affect the extent to which automation procedures can identify a line or set of lines as associated with a particular river. They include:

- connectedness – lines are not joined at confluences (Figure 4.2 A)
- direction – lines do not all ‘point’ or ‘flow’ in the same direction (Figure 4.2 B)
- duplication – water bodies and wide rivers are depicted on maps as double lines, following the banks of the feature (Figure 4.2 C)
- attributes – the scanning and vectorising process could not add attributes such as river name, Strahler order, associated catchment number, etc

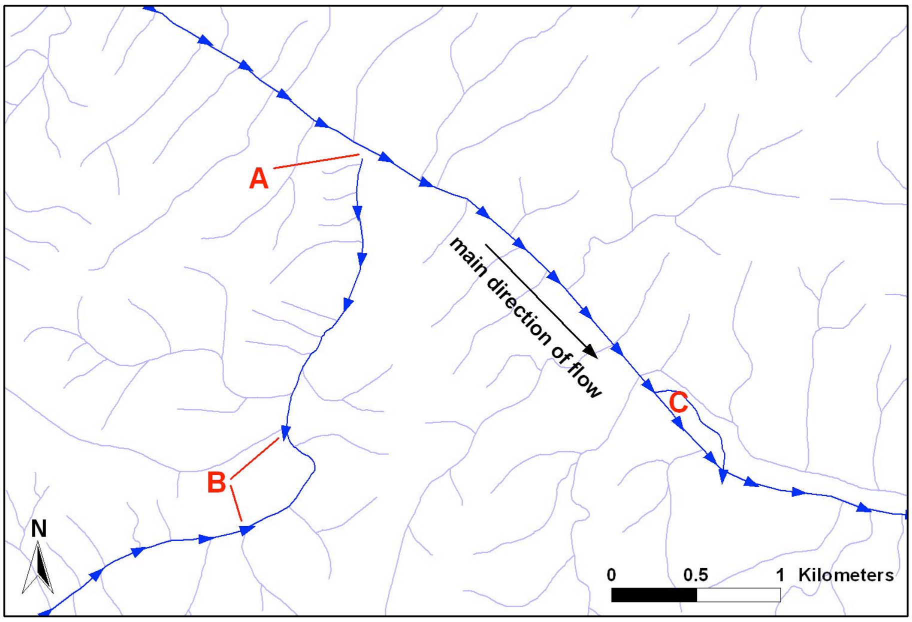


Figure 4.2: Examples of issues of connection (A), direction (B) and line duplication (C)

4.2.2.3 Addressing the issues

Only the **1:50 000** features required to create a reference dataset for comparison in the X catchment were extracted from the national 1:50 000 river lines. Minimal pre-processing of the original scanned river lines has taken place and considerable manual intervention was required before they were in the right format for the routing and distance calculations required in this study:

- river line segments corresponding to each river line segment in the 1:500 000 data set are extracted
- connections are formed between these sections by manually adding single lines (e.g. through water bodies) or snapping adjoining lines to each other
- each segment direction is checked and, if necessary, reversed so that all the segments point/flow in a downstream from-to direction
- limited generalisation is applied to remove excess nodes produced during the connecting process
- to minimize the workload, no extra attributes were added to the new 1:50 000 river lines

The original vectorised **1:500 000** lines have been modified manually previously at Department of Water Affairs: Directorate Resource Quality Services to address the issues listed above in section 4.3.2 and to produce a standard rivers data set which can be used at a national scale and has been improved to facilitate its use in automatic GIS routines (DWAF, 2006). No pre-processing was required for this study. However, the steps originally followed to create the existing national data set are listed here to illustrate the complexity that would be required to upgrade the national 1:50 000 river lines to the same level. This list also illustrates the amount of extra functionality that has been added to the scanned 1:500 000 lines enabling to be used in automated procedures for national assessments of South African rivers:

- topology – ensured all river sections were connected at confluences and pointing in a downstream direction
- improve locational accuracy of the lines by manually adjusting each section to be horizontally within 50m of the corresponding stream on the 1:50 000 map sheets. If plotted at a 1:50 000 scale, these adjusted 1:500 000 river lines are within 1mm of the 1:50 000 mapped river lines. The results of these manual adjustments are illustrated in Figure 4.3.
- resolved discrepancies between river lines at map edges
- added a centerline where duplicate lines were scanned along river banks and at dams
- confirmed river names and spelling
- used supplementary datasets from the Digital Chart of the World (Danko,1992) available online to add connecting rivers from neighbouring countries
- ensured that there is at least one river line per quaternary catchment

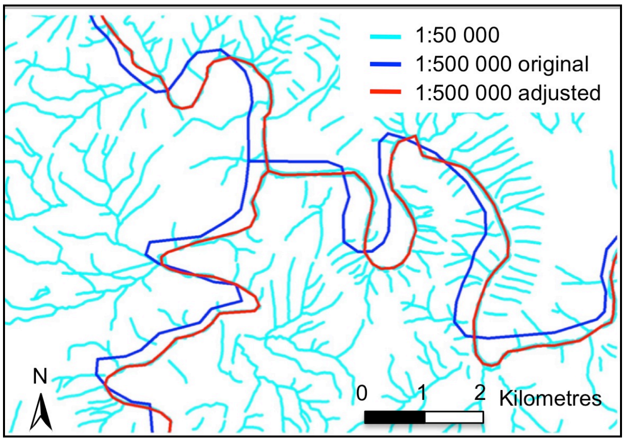


Figure 4.3: 1:500 000 river lines adjusted to match 1:50 000 river lines

Once the 1:500 000 lines were topologically and horizontally adjusted an automated procedure was used to assign a number of attributes (DWAF, 2006):

- a unique reachcode is assigned to each stream segment to identify it within the total dataset
- a unique code is also assigned to identify each segment within a primary catchment
- all rivers were classified according to the Strahler stream ordering system
- each segment is identified according to whether it is a start (no upstream connection), intermediate (connected upstream and downstream) or end line (no downstream connection). Endorheic (no upstream or downstream connection) streams are also identified
- Create a text file per source stream that contains a list of the downstream connecting reachcodes starting at each source stream and ending at the sea, i.e. where no more downstream connections can be made. These are the files used in this study to automatically extract connected lines representing each existing river.

Figure 4.4 illustrates the attributes added to the river lines. The value of the adjusted and attributed 1:500 000 data set for this study is in the unique reach codes and the downstream connections that are established and stored in the text files. This makes it possible to select line segments associated with an existing river and join them together into an individual line per physical river. Longitudinal profiles can then be extracted per existing river. This is an advantage that is unique to the set of 1:500 000 river lines, and has not been included as a requirement for the ‘corrected’ 1:50 000 river lines, when they become available (Twyman, 2011).

One hundred and forty three existing rivers are represented in the scanned 1:500 000 scale river lines in the X primary catchment. Each main river line is made up of a set of joined river lines pointing in a downstream flow direction, mostly attributed with a name to identify it. They are referred to as ‘main stems’ in this study.

For the purposes of this study a comparison is undertaken between the lengths of these main stems as measured from the 1:50 000 scanned river lines and the lengths measured from the adjusted 1:500 000 river lines. One hundred and nine main stem lines are included in the comparison. Six out of the 109 main stems have a length difference of more than 1km between the 1:50 000 lines and the 1:500 000 lines. In four of these six, this amounts to more than 1% difference over the total length of the river main stem (i.e. more than 1km over a distance of 100km). These differences are ascribed to two factors: misalignment at the eastern edge of the catchment where the 1:50 000 scanned rivers do not extend as far as the 1:500 000 scanned rivers; and some generalization of the 1:500 000 through Kwena Dam and Witklip Dam. Ninety-five percent of the main stems compared have a difference in measured length of less than 1km.

4.2.3 Contours

1:50 000 scale map sheets are available from CDNGI for the entire South Africa in both paper and digital form. The individual color plates making up these map sheets have been scanned and vectorised. The contour lines from these sheets are available from CDNGI in ESRI™ shapefile format. They have a vertical interval of 20m. The contour lines are combined with the 1:50 000 river lines to provide the elevations required to produce a reference data set of longitudinal river profiles for this study.

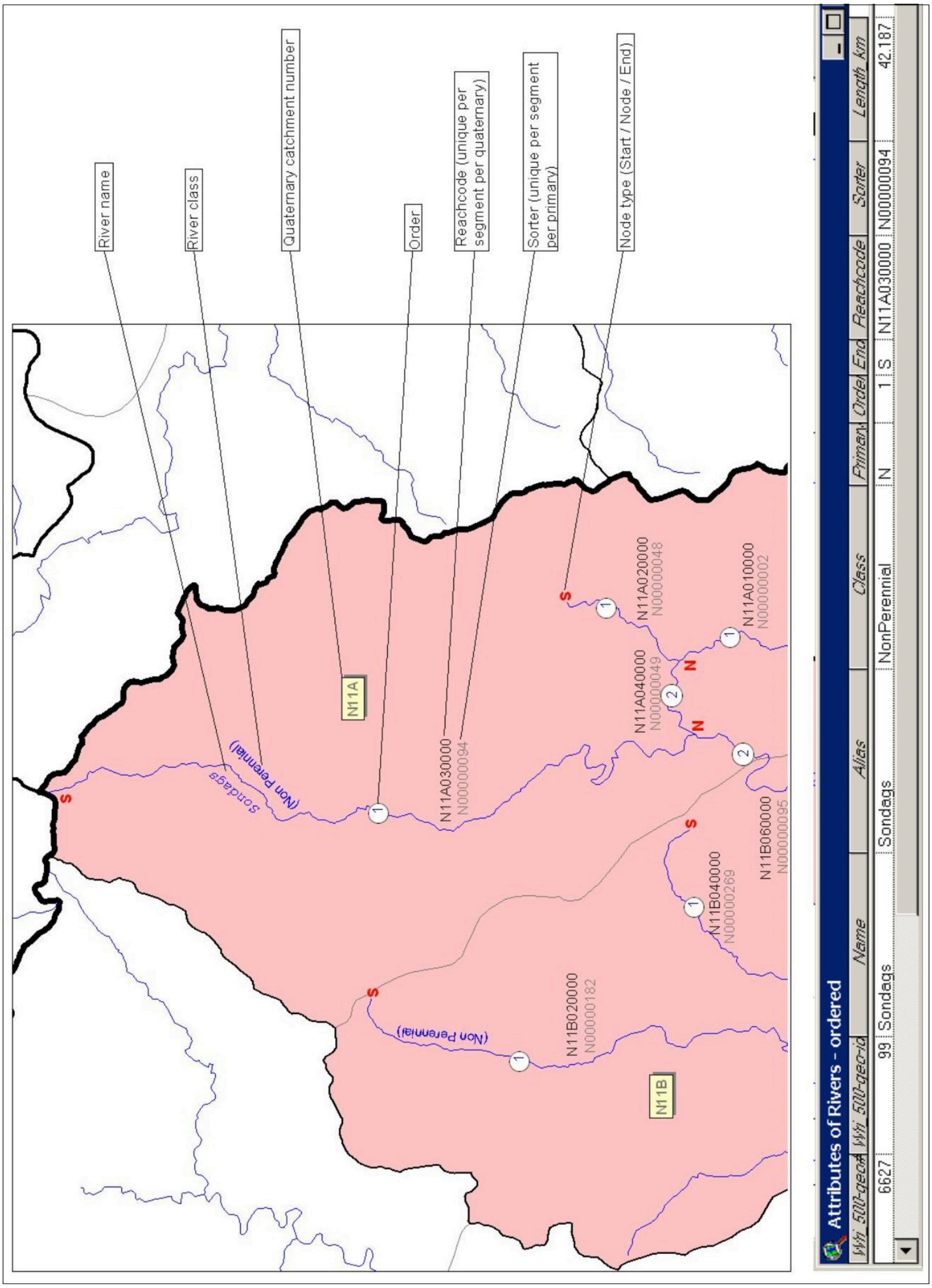


Figure 4.4: Attributes of 1:500 000 rivers data set available from DWA (after DWAF, 2006)

4.3 Methodology

The purpose of this section is to describe the methods used to achieve the required comparisons. The research is designed around the comparison of slopes along river longitudinal profiles calculated from elevations and distances derived from various sources. Profiles obtained from three Digital Elevation Models (DEMs) and 1:500 000 scale rivers, are compared to slopes derived from 1:50 000 contours and 1:50 000 river lines. All spatial analyses undertaken in this study implement the ESRI (2006) suite of GIS software.

4.3.1 Research Design

Historically river longitudinal profiles are derived by extracting the required distance and elevation values from topographic maps showing river lines and contours. In South Africa, the 1:50 000 scale map sheets were used most frequently. Distance was measured sometimes as coarsely as laying a piece of string along the streamline and marking where it crossed a contour to include elevations. For this study distance is measured by linear referencing techniques in a GIS with the contour intersections treated as events along the length of the stream.

Digital rivers and contours captured from the 1:50 000 maps are intersected to obtain the distances and elevations required to draw a longitudinal profile of a river. These values form the baseline for comparison with profiles derived from DEM20, DEM90 and DEM200 using distances measured from the 1:500 000 rivers and elevations measured from the three Digital Elevation Models described in the previous section. The basic analysis procedure is shown in Figure 4.5. The set of distances and associated elevations determined along the length of a river will form a longitudinal profile, which can be used to interpolate an elevation at any distance along the profile. This profile and its associated set of data values can also be used to calculate a slope between any required two points along the profile. There are thus two derivatives from the river longitudinal profile:

- a first order derivative, elevation, and
- a second-order derivative, slope

It is these derivatives (elevation and slope) that are used to undertake a statistical comparison by comparing elevations and slopes derived at the same points (distances) along the profile. Two main sets of distances are used for the basis of comparison in this study:

- distance as measured along the 1:50 000 streams and corresponding to the intersection of the 1:50 000 stream with 1:50 000 contours
- distance at regular intervals along the length of the profile (100m intervals, 200m intervals, 300m intervals, 400m intervals and 500m intervals)

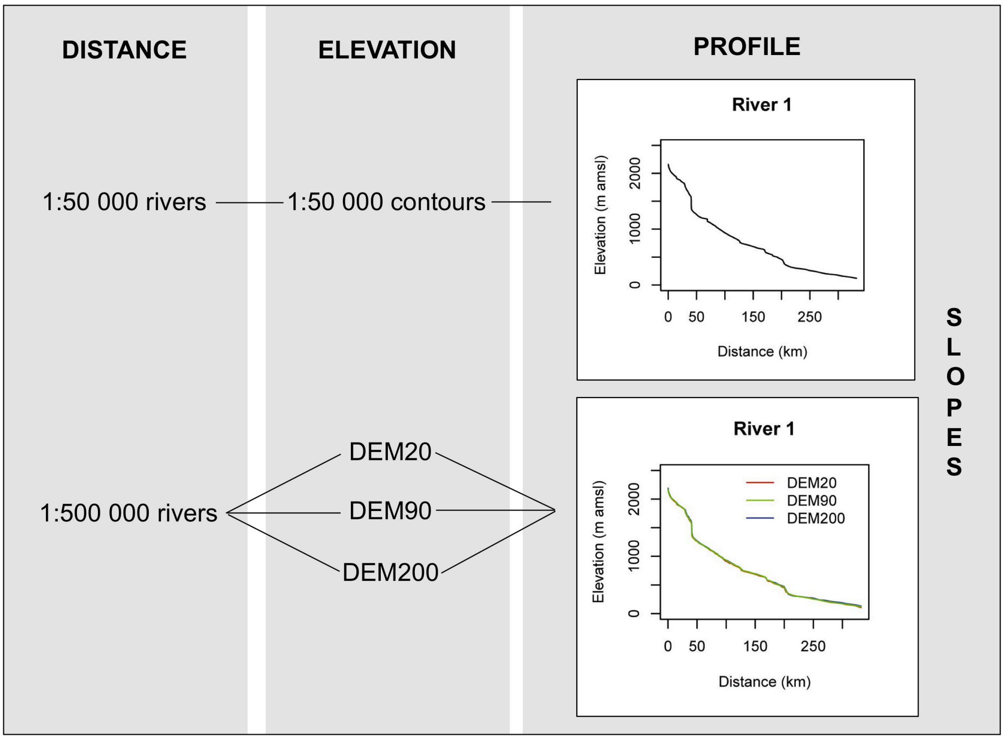


Figure 4.5: Diagrammatic view of comparisons between 1:50 000/contour-derived profiles and 1:500 000/DEM-derived profiles

In this way a profile-based comparison can be undertaken between the elevations and slopes derived traditionally from 1:50 000 contours and streams, along with those derived by overlaying the 1:500 000 adjusted South African rivers with DEM20, DEM90 and DEM200. The Wilcoxon-Mann-Whitney test (Snedecor and Cochran, 1980) is used to assess the extent of similarity between the four data sets.

4.3.2 Procedure

The comparative analysis requires (a) a profile derived from 1:50 000 river/contour intersections, and (b) a set of profiles derived from a DEM. Separate methodologies are required for each of these two sections of the analysis. The process is applied iteratively for each of the 143 identified rivers (main stems) in the catchment.

4.3.2.1 1:50 000 rivers and contour-based profiles

A reference data set is created for this study by intersecting 1:50 000 river lines with 20m interval contour lines using a GIS. Once all the 1:50 000 river lines are correctly aligned and connected, as described above, and each stored in a separate shapefile, it is possible to automate the rest of the procedure in ArcGIS using a Python script developed for this study. The script automates the following steps:

- assign route topology to each river
- perform a vector on vector overlay with the contours of the X catchment
- extract the river-contour intersection points to a separate shapefile for each river/main stem, retaining the contour HEIGHT value of each intersection as a field in each shapefile
- use these intersection points as events on the river line to assign a cumulative distance value for each river-contour intersection along the river, starting at the source
- write the cumulative distance and associated elevation values to a text file, from where they can be used to generate a longitudinal profile

As an example, the actual location of these values are plotted on a 1:50 000 map sheet (obtained from CDNGI) on the Crocodile River in Figure 4.6. The equivalent positions in terms of elevation and distance along the longitudinal profile are also illustrated in Figure 4.6.

4.3.2.2 1: 500 000 rivers and DEM-based profiles

Since the 1:500 000 river lines are already available as connected, downstream-pointing lines, it is possible to use the DEMs and the rivers as input to an automated process to produce a data file of elevations at intervals along the length of each required river. There are six main steps required to obtain the longitudinal river profiles and assess the extent of ‘sameness’ between them:

- identify the river line
- derive various profiles by extracting distances and elevations to a text file:
    - overlay each river main stem on the DEM to get distances and elevations
    - overlay each river main stem on the DEM to extract distances and elevations at 1:50 000 contour intersection points
- smooth the DEM profile
- interpolate profile elevations at 100m, 200m, 300m, 400m and 500m horizontal distance intervals
- calculate slopes between contour intersection points based on the distance between contours along the river
- calculate slopes at the 100m to 500m horizontal distance intervals

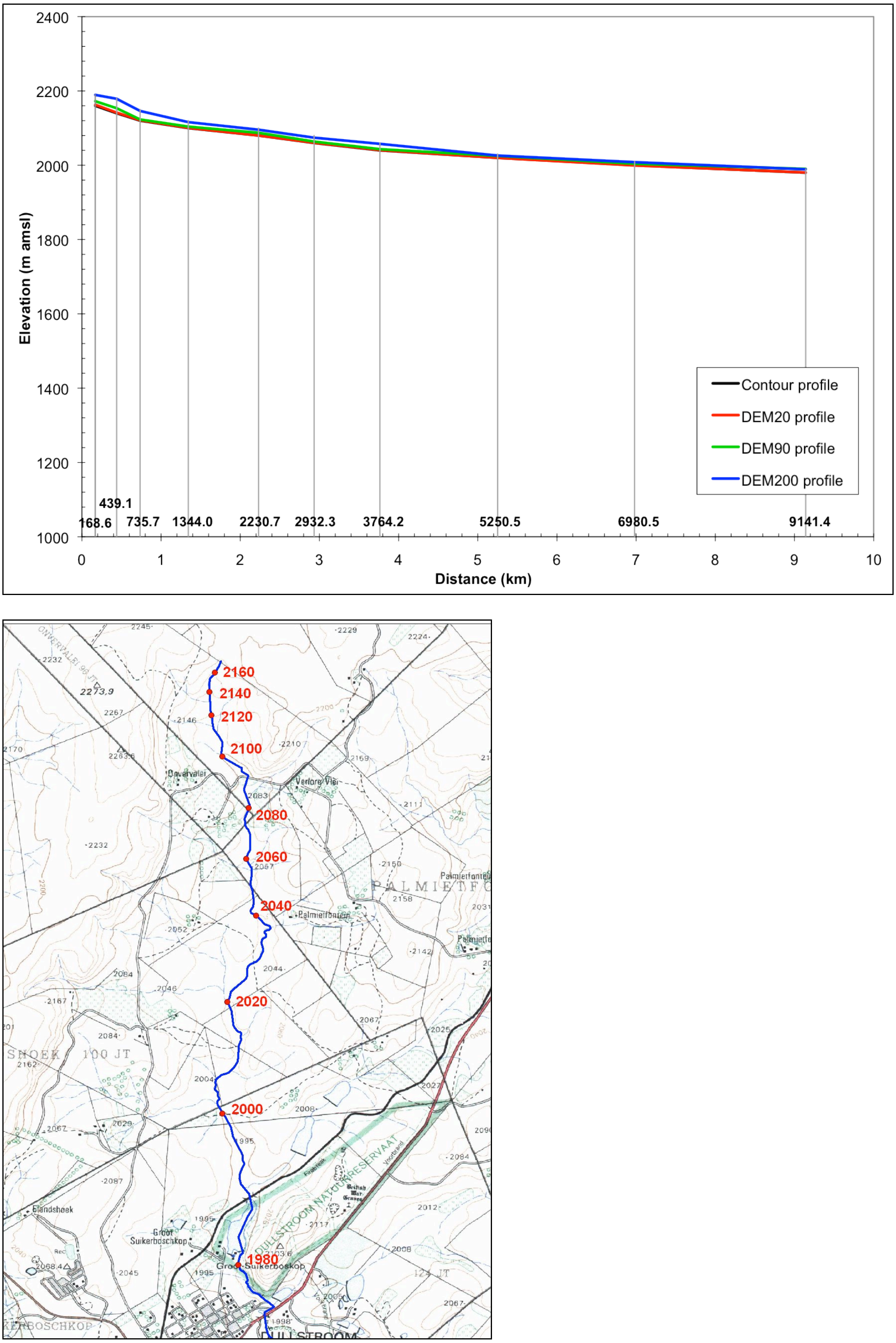


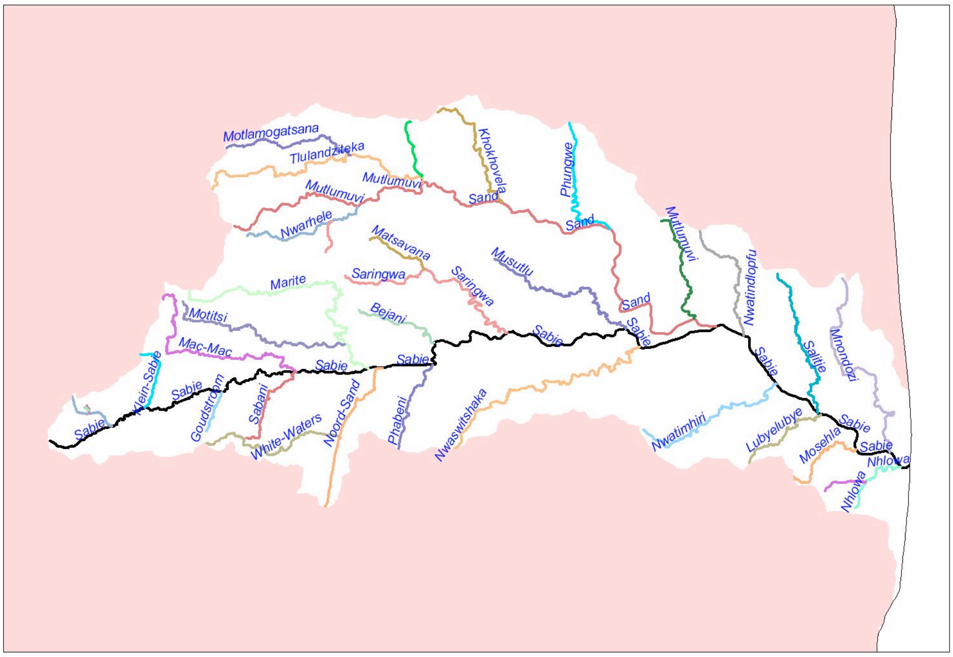
Figure 4.6: River-contour line intersections along the Crocodile River

These steps are currently incorporated into a semi-automated procedure comprised of a suite of Arc/INFO AML macros designed to undertake the following steps:

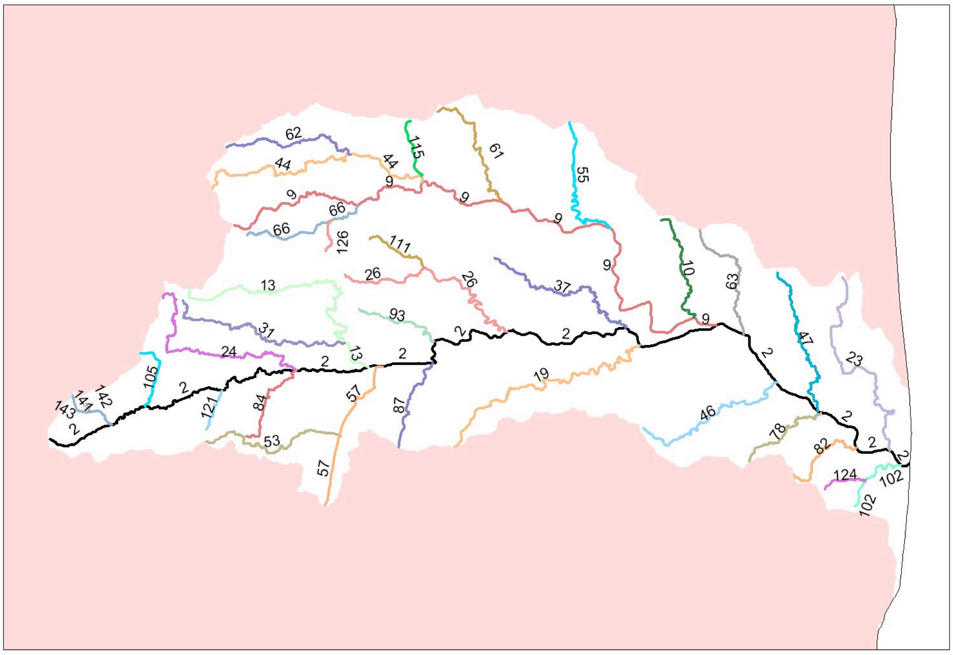
- generate a text file listing all start reaches
- identify and number each unique river main stem, based on the identified start reaches
- extract the longitudinal river profile for each river line
- smooth the peaks from the longitudinal profile
- identify unique river main stems

The first step in deriving a longitudinal profile for a river is to identify the main segments that comprise each 1:500 000 river. Commonly rivers are identified by name, however it is not unusual to find a river name changing along its length from source to sea. Although continuity based on river names is taken into account, river main stems are finally labeled with a unique number identifier (REACHNUM) as illustrated in Figure 4.7 (a) and Figure 4.7 (b) for the Sabie River catchment in Mpumalanga, which is part of the X primary catchment.

Rivers main stems are initially sorted according to name and length. The start reach (source stream) of each river is recorded in a text file, with the start reaches of the longest named rivers being recorded first and source reaches without name being recorded last. Given the source reaches of each river in a catchment it is possible to trace the segments of the river consecutively in a downstream manner based on the REACHCODE links set up by DWAF (2006). Each individual river line/main stem identified in this manner is assigned a unique number (REACHNUM) and is comprised of a set of REACHCODE segments combined in a downstream direction until either an 'end' REACHCODE is reached, or the confluence with a river that already has a REACHNUM. This procedure is applied to all the adjusted 1:500 000 rivers with the range of REACHNUMs extending from 1 to the number of unique main stems in the catchment. One hundred and forty-three unique river lines are identified in primary catchment X. Figure 4.7 (b) shows the subsection of these occurring in the Sabie River secondary sub-catchment of the X catchment.



4.7 (a)



4.7 (b)

Figure 4.7: River names and main stem numbers for 1:500 000 rivers

Once river main stems have been identified, the next step is to derive the longitudinal profiles. Figure 4.8 shows the steps in the algorithm to derive the river longitudinal profile. Although currently a suite of Arc/INFO AML macros is used to automate the process, the algorithm shown in Figure 4.8 could easily be converted into a set of steps to be followed in ArcGIS or automated into a Python script.

- The first step is to assign route topology to the set of connected segments comprising a river (based on REACHNUM), starting at the river source segment

- If using an AML it is necessary to check the total river length to determine an appropriate profile interval (river length / 500) since Arc/Info coverage constraints only allow 500 vertices (points) per arc/line.
- Derive the river longitudinal profile from the DEM. As an ArcINFO™ coverage, sections of the profile are not sorted in a downstream consecutive manner, but according to the internal number of each arc comprising the river. Therefore, the following three steps are required:
    - export the x,y co-ordinates of the profile to a file
    - use these x,y's to generate a coverage of points at equal intervals along the length of the river
    - determine the elevation of the DEM at each profile point
- Use the route topology to derive the distance of each profile point from the river source
- Output a data file consisting of distance from source *vs* elevation

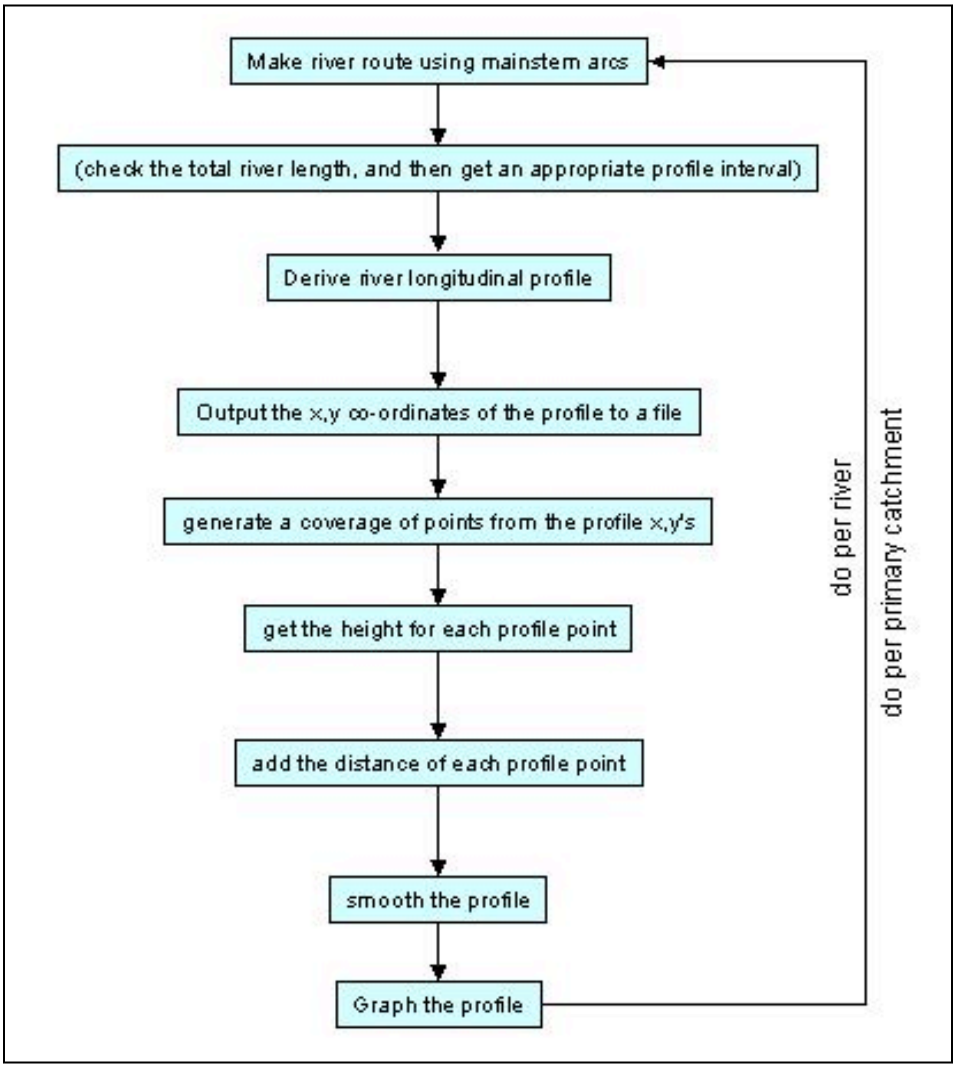


Figure 4.8: Procedure used to determine river longitudinal profiles

After extracting the values comprising the profile, the final main task is to smooth this derived profile. The river profile produced will include a number of peaks as illustrated in Figure 4.9 for the Elands River in Mpumalanga. These are the result of differences in resolution and scale between the river line and the DEM, shown in Figure 4.10. As a result of this the scanned river line doesn't exactly match the valley bottom identified by the DEM.

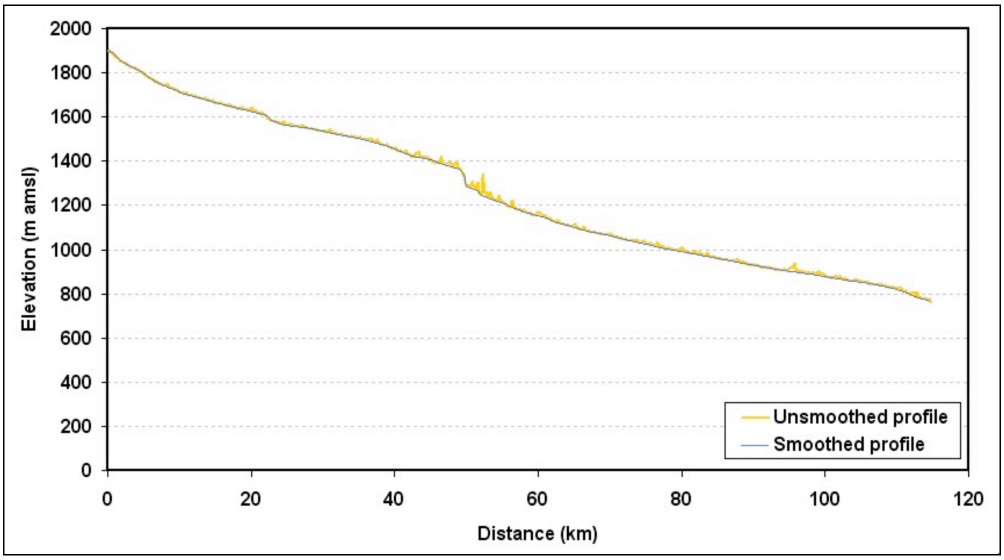


Figure 4.9: Unsmoothed and smoothed profiles of the Elands River

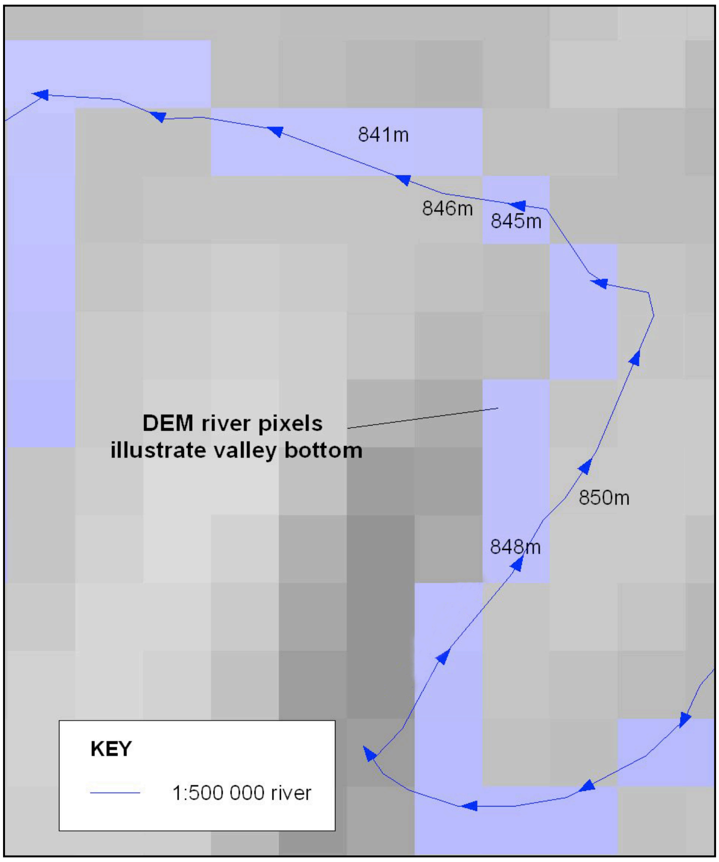


Figure 4.10: Comparison between 1:500 000 river line and valley bottom values - DEM90

These points are removed by further processing the data using a script to extract only the lowest points along the length of the profile (assumed to represent the valley/channel bottom), thereby creating a monotonically decreasing profile. The final output is a text file (Table 4.2) of distances and elevations from the source of the river, downstream to the mouth or confluence with the next large river. This data can then be further classified or analysed as required.

Segment ID	DISTANCE (m)	ELEVATION (m)
1	0	2043
2	49	2032
3	100	2023
4	113	2021

Table 4.2: Part of a river table showing distance along the length of the river main stem, and the associated elevation at each distance

4.3.2.3 Interpolate slopes

In general terms, the slope of each profile segment is measured as the vertical change in elevation over the horizontal change in distance (Equation 4.1). The slope is calculated in the direction of flow (Figure 4.11): starting at the river source and ending at the river mouth. Since elevation decreases as distance from the source increases, the calculated slope will always be negative. For ease of reading and calculation the absolute value of the slope is used in this study. Therefore, all slopes presented in this study should be read as decreasing, despite the absence of the negative sign.

$$\text{Slope (\%)} = \left| {(y_2 - y_1)}\big/{(x_2 - x_1)} \right| * 100 \qquad \text{(Equation 4.1)}$$

where:

y_1 = upstream elevation

y_2 = downstream elevation

x_1 = upstream distance

x_2 = downstream distance

Slopes in this study are presented as percentages. For comparison, a 100% slope is equivalent to an angle of 45°, and translates to a vertical change of one over a horizontal change of one (1/1).

Figure 4.11 shows how a slope calculation would relate to the longitudinal profile of a river. In each scenario the distance values along the X-axis are kept constant and elevation values are extracted at the associated profile Y.

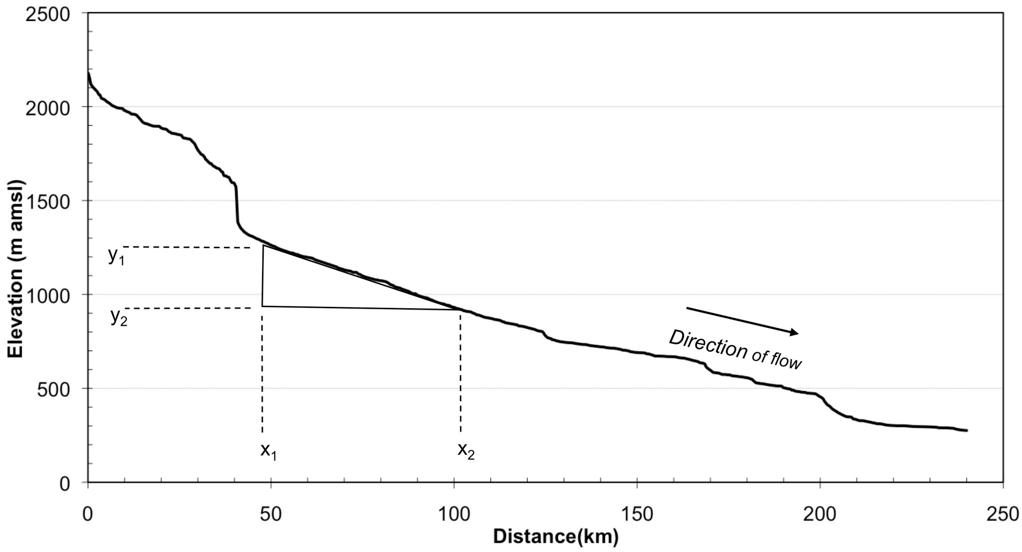


Figure 4.11: A slope segment measured on a longitudinal river profile

4.3.3 Statistics

This section describes the statistical tests used to assess similarity between the elevation and slope values collected from the contour maps and the DEMs. A number of R scripts were developed to support the required statistical analyses. R is a scripting language that provides support for statistical analysis and graphics (R, 2010), making it possible to automate analyses and display the results graphically.

4.3.3.1 Assumptions

The choice of statistical test for the analysis needs to satisfy two main assumptions.

In the first instance, the profile values are structured as a series of pairs with each contour-derived elevation or slope having a DEM-derived equivalent at the same cumulative distance along the profile. Any statistical technique used to compare these series needs to retain this paired characteristic of the data.

Secondly, the test chosen must suit the underlying distribution of the data. Many statistical tests assume that the underlying data population is normally distributed and before choosing a test it is important to assess the underlying data distribution. The Shapiro-Wilk test is used to test whether the elevation and slope values can be assumed to come from a normal distribution (R, 2010). The following data sets are assessed:

- combined elevations for all rivers in the X catchment as extracted from 1:50 000 maps at 1:50 000 river/contour intersections
- combined slopes for all rivers in the X catchment based on elevations extracted from 1:50 000 maps at 1:50 000 river/contour intersections
- combined elevations for all rivers in the X catchment as derived from a 20m, a 90m and a 200m resolution DEM at 1:50 000 river/contour intersections

- combined slopes for all rivers in the X catchment based on elevations extracted from a 20m, a 90m and a 200m resolution DEM at 1:50 000 river/contour intersections
- combined elevations for all rivers in the X catchment extracted from the 20m, 90m and 200m DEMs; at 100m, 200m, 300m, 400m and 500m intervals along each river longitudinal profile
- combined slopes for all rivers in the X catchment based on elevations extracted from the 20m, 90m and 200m DEMs; at 100m, 200m, 300m, 400m and 500m intervals along each river longitudinal profile.

The results are shown in Table 4.3 and Table 4.4. In all cases a p-value close to 0 is reported. This suggests that it is reasonable to assume that the test null hypothesis that the data is normally distributed, can be rejected at both the 95% ($p < 0.05$) and 99% ($p < 0.01$) percent confidence levels. There is therefore significant evidence to accept the alternative hypothesis that the data does not come from a normal distribution.

Table 4.3: Results of the Shapiro-Wilk test for elevation and slopes based on contour intersections

	Elevation Shapiro-Wilk W	**Elevation** p-value	**Slope** Shapiro-Wilk W	**Slope** p-value
1:50 000 contour	0.97351	1.40E-23	0.5599507	1.38E-66
DEM20	0.97345	1.32E-23	0.6487056	2.60E-62
DEM90	0.97249	5.22E-24	0.5896845	2.98E-65
DEM200	0.97040	7.52E-25	0.6932133	8.39E-60

Table 4.4: Results of the Shapiro-Wilk test for elevations and slopes interpolated at increasing equal horizontal distance intervals

	Elevation W	**Elevation** p-value	**Slope** W	**Slope** p-value
100m interval				
Contour	0.88271	3.88046E-27	0.33081	1.06997E-67
DEM20	0.88282	4.24645E-27	0.38012	4.89202E-66
DEM90	0.88290	3.23885E-27	0.40315	1.14173E-65
DEM200	0.88255	4.83432E-28	0.42635	1.32489E-65
200m interval				
Contour	0.90525	4.37844E-27	0.36062	4.2919E-53
DEM20	0.90570	1.34186E-26	0.40802	4.52499E-52
DEM90	0.90527	3.58171E-27	0.38589	6.21699E-52
DEM200	0.90575	2.97395E-27	0.42312	3.78621E-51
300m interval				
Contour	0.90713	5.42978E-23	0.40871	2.06033E-45
DEM20	0.90698	5.24317E-23	0.44515	2.61795E-44
DEM90	0.90674	3.34722E-23	0.44223	5.37805E-44
DEM200	0.90741	2.74908E-23	0.48519	2.03176E-43
400m interval				
Contour	0.90790	4.44686E-20	0.44557	1.51789E-40
DEM20	0.90769	4.29699E-20	0.48403	1.14051E-39
DEM90	0.90767	2.90528E-20	0.48705	3.72875E-39
DEM200	0.90800	2.24832E-20	0.51699	7.68423E-39
500m interval				
Contour	0.90343	4.15614E-35	0.43722	1.54508E-58
DEM20	0.90319	3.99157E-35	0.46561	1.32624E-57
DEM90	0.90352	4.83972E-35	0.46186	9.69867E-58
DEM200	0.90410	6.80285E-35	0.50098	4.21005E-56

The frequency plot can be used as a visual method of assessing whether the data is normally distributed. Figure 4.12 shows a frequency distribution of all elevation values based on contour intersections, with the majority of values showing a bias to the right of the mean elevation of 1087.5. Figure 4.13 shows a frequency distribution of all slope values based on contour intersections. It illustrates a strong skewness towards low slopes. The conclusion is that the data is not normally distributed and a nonparametric test must, therefore, be used to perform statistical comparisons between the data sets.

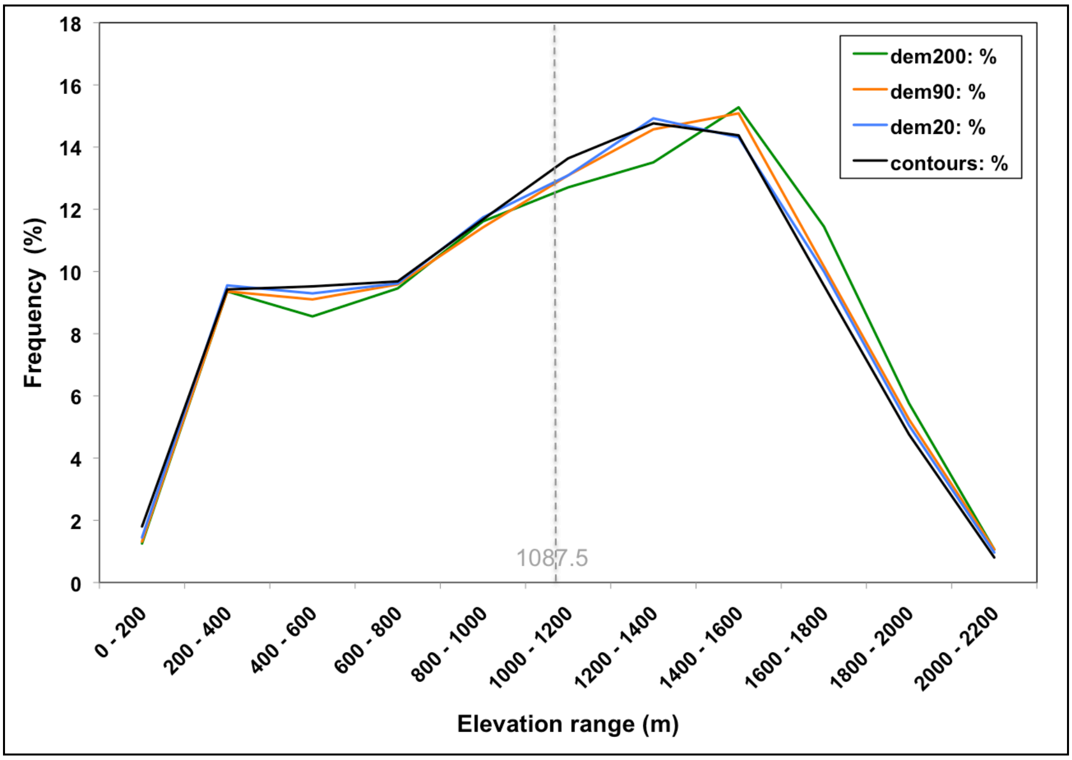


Figure 4.12: Percentage of elevation values plotted according to elevation range (n=3109)

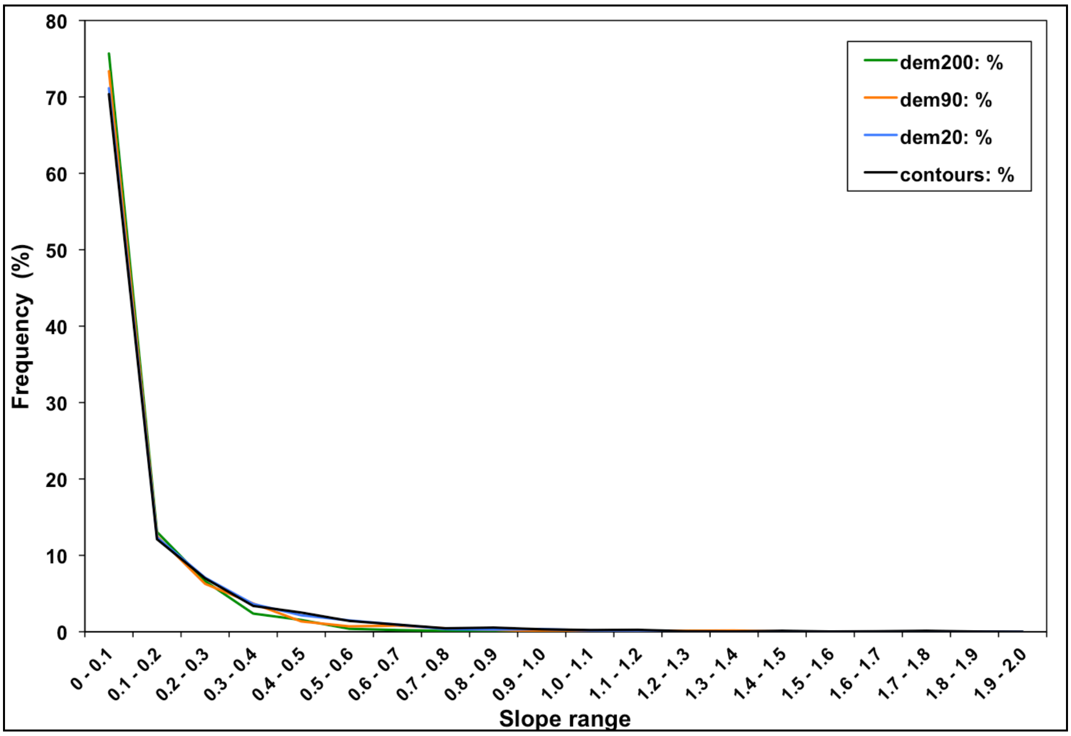


Figure 4.13: Percentage of slope values plotted according to slope range (n = 3108)

4.3.3.2 Tests

Given that the elevation and slope data sets cannot conclusively be assumed to come from a normally distributed population the non-parametric Mann-Whitney-Wilcoxon test is selected for statistical investigations. This test ranks all the values of the two data sets being compared. It then determines how many values of each data set are exceeded (in rank) by values of the other data set. The sum of these ranks for each set of data will then give an indication whether one data set generally tends to have values consistently higher or lower than the other. According to Snedecor and Cochran (1980) the null hypothesis for the Mann-Whitney-Wilcoxon test states that one of the two data sets does *not* have consistently higher/lower values than the other (i.e. the distribution of values is the same). The alternative hypothesis for the test states that one of the data sets has a distribution of values that *is* higher/lower than the other.

The Mann-Whitney-Wilcoxon test aims at comparing two independent samples. However, given that the elevations and slopes being compared in this study are derived at the same geographical location, independence cannot be assumed. A variation of the Mann-Whitney-Wilcoxon rank sum test based on matched pairs (also known as the Wilcoxon signed rank test), which allows for dependence between samples (Snedecor and Cochran, 1980), is implemented in this case. This test ranks the differences between each pair of values and then sums the ranks for the positive and negative differences individually. The wilcox.test function in R (R, 2010) is used to perform the test in this study. It outputs a test statistic (called V in this instance) and a p-value for each set of profiles. The null hypothesis for this particular test states that the negative and positive differences between the sample pairs are symmetrically distributed about the mean i.e. again, neither data set is consistently higher or lower than the other (R, 2010). The test statistic V reports on the sum of the ranks of the positive differences.

Appendix A gives a manual example of the procedure followed for the Mann-Whitney-Wilcoxon signed rank sum test based on matched pairs. REACHNUM 113 is used to present the example.

4.4 Summary

The methods of data collection and data comparison have been described in this chapter. Elevation and slope values describing river longitudinal profiles are extracted from 1:50 000 contours and from 20m, 90m and 200m Digital Elevation Models, based on 1:50 000 and adjusted 1:500 000 scanned river lines. These values will be examined and compared and the results presented in Chapter 5.

CHAPTER 5
RESULTS

5.1 Introduction

In this chapter the methods described in previous chapters are applied to the river main stem lines in primary catchment X in eastern South Africa. The catchment comprises 143 rivers when considered at 1:500 000 scale, with 109 rivers satisfying all the conditions for comparison. The reference data set in each case is the profile derived from elevations extracted at 1:50 000 river line/contour intersections. The DEM-derived profiles based on 1:500 000 river lines are then compared to these. Two main reference scenarios are considered, with a total of six methods of comparison as sub-sections to these scenarios:

- Scenario 1: Elevation and slope measured along a 1:50 000 river main stem line. Elevations are extracted at the intersections of each 1:50 000 river main stem line with 1:50 000 contours to generate longitudinal profiles
- Scenario 2: Elevation and slope interpolated at regular intervals along the length of the 1:50 000 main stem profiles derived for Scenario 1 (100m intervals, 200m intervals, 300m intervals, 400m intervals and 500m intervals)

These reference profiles are then compared to longitudinal profiles and slopes based on the adjusted 1:500 000 main stems and elevations derived from DEM20, DEM90 and DEM200.

A visual as well as a statistical comparison is undertaken. The Mann-Whitney-Wilcoxon test is used to statistically assess the similarity between sets of elevations and slopes calculated between interpolated sections along the river longitudinal profiles.

5.2 Conditions for comparison

The two main conditions limiting the comparison of stream profiles are input data overlap and sample size.

5.2.1 Input data overlap

Portions of the rivers in the southern parts of the catchment flow through Swaziland. Neither the contours nor the 20m resolution DEM derived from the contours, extends beyond the borders of Swaziland. Contours are an essential input since they are the baseline according to which all comparisons are being made. It was therefore decided to exclude all river main stems for which contours are not available for the entire length of the line. Profiles are available for the sections of these main stems that do fall within the borders of South Africa, but have not been included in the analysis in this study.

Figure 5.1 shows the extent of the 1:50 000 contours for South Africa and DEM20 in the southern parts of the catchment. Twenty-two rivers (shown in Figure 5.1) flowing in or through Swaziland are excluded from analysis, including the Komati and Lomati Rivers.

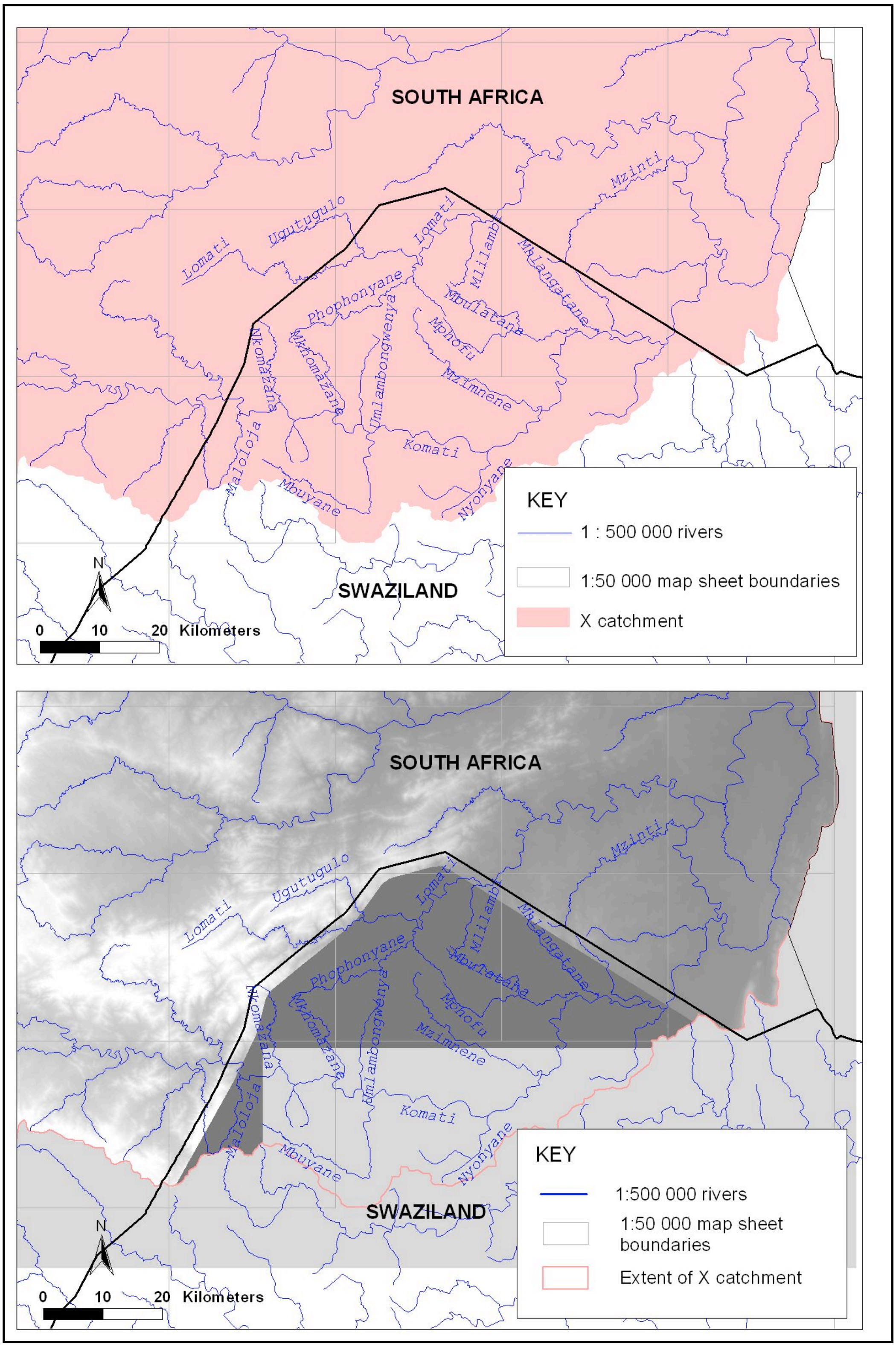


Figure 5.1: Extent of contour and DEM20 data at the Swaziland border with the X catchment

5.2.2 Sample size

Generally a sample of size of 30 is considered as a minimum for statistical analyses (Rumsey, 2003), however R (R, 2010) provides for sample sizes as small as five to be used by the Mann-Whitney-Wilcoxon test. The number of observations along a longitudinal profile will vary according to the number of river line/contour line intersections, or the horizontal interval being used to interpolate elevations and slopes along the profile. The longer the horizontal distance between observations, the fewer the number of observations. Examination of the river main stems and their associated number of observations showed that one river is less than 900m in length - intersecting only two 1:50 000 contours approximately 400m apart. Eight more profiles have fewer than five contour intersections. Three river main stems have more than five contour intersections but are not long enough to have more than five sampling points in the 300m, 400m and 500m horizontal interval analysis.

Altogether twelve profiles are therefore excluded from the final analysis on the basis of too few sampling points. However it must be noted that although profiles with as few as five sampling points are retained for analysis, as sample size decreases so does the confidence with which any comparisons can be made (R, 2010). Table 5.1 lists the distribution of observations for the six types of comparison that will be undertaken.

Table 5.1: Distribution of sample sizes used in the final analysis

Sample size	Contour intersections	Horizontal intervals				
		100m	200m	300m	400m	500m
5 - 10	28	0	1	0	0	1
11 - 30	36	0	2	7	18	27
31 - 50	31	1	8	21	31	33
51 - 100	12	11	39	38	32	31
101-1000	2	91	58	42	28	17
> 1000	0	6	1	1	0	0

5.3 Input river lines

Based on the above ‘Conditions for comparison’ the profiles of 109 river main stems meet the requirements for analysis. This final set of river lines is shown in Figure 5.2. The river main stems that have been excluded for the reasons mentioned above are not included in this table. Main stems are referenced by REACHNUM, a label used to uniquely identify each river. The name of each river and its associated REACHNUM is given in Table 5.2. River names are consistent with those used on the 1:50 000 topographic map sheets. Nine have not been labeled on the 1:50 000 maps. These unlabeled rivers are included, in grey, at the end of Table 5.2.

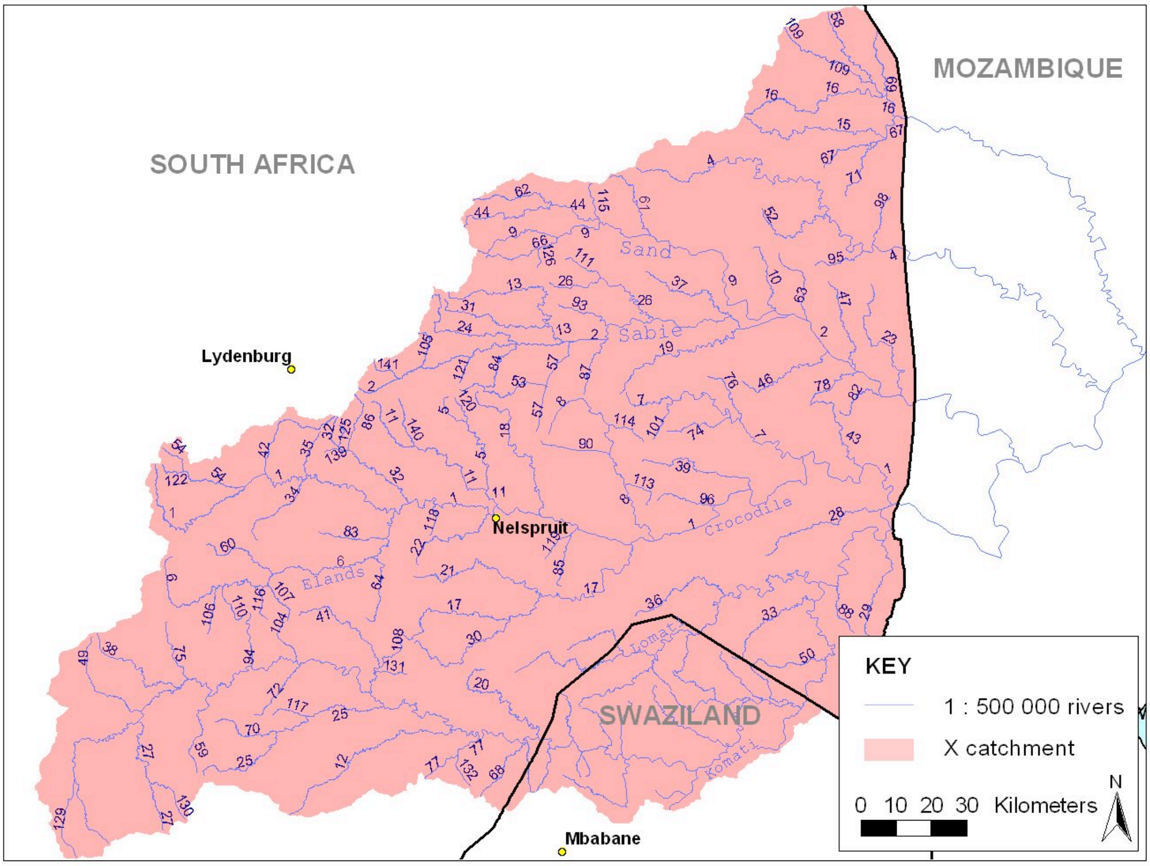


Figure 5.2: 109 main stem rivers of the X catchment labeled according to REACHNUM

Table 5.2: A list of river names and REACHNUMs for the X catchment

NAME	REACH -NUM	NAME	REACH -NUM	NAME	REACH -NUM
Crocodile	1	Klein-Komati	38	Sabani	84
Sabie	2	Mlambeni	39	Blinkwater	85
Nwaswitsontso	4	Gladdespruit	41	Blystaanspruit	86
Sand	5	Alexanderspruit	42	Phabeni	87
Elands	6	Vurhami	43	Mambane	88
Mbyamiti	7	Nwandlamuhari	44	Gutshwa	90
Nsikazi	8	Nwatimhiri	46	Bejani	93
Mutlumuvi/Sand *	9	Salitje	47	Bankspruit	94
Mutlumuvi *	10	Witkloofspruit	49	Shilolweni	95
Nels	11	Mgobode	50	Matjulu	96
Teespruit	12	Ripape	52	Metsimetsi	98
Marite	13	White-Waters	53	Komapiti	101
Sweni	15	Lunsklip	54	Gemakstroom	104
Nwanedzi	16	Noord-Sand	57	Klein-Sabie	105
Suidkaap/Kaap	17	Gudzani/Mavumbye	58	Leeuspruit	106
Wit	18	Swartspruit	59	Weltevredespruit	107
Nwaswitshaka	19	Swartkoppiespruit	60	Poponyane	108
Mtsoli	20	Khokhovela	61	Mavumbye	109
Noordkaap	21	Motlamogatsana	62	Rietvleispruit	110
Gladdespruit	22	Nwatindlopfu	63	Matsavana	111
Mnondozi	23	Ngodwana	64	Mnyeleni	113
Mac-Mac	24	Nwarhele	66	Sithungwane	114
Buffelspruit/Seekoeispruit	25	Mrunzuluku	67	Mphyanyana	115
Saringwa	26	Mlondozi	68	Joubertspruit	116
Boesmanspruit	27	Shinkelengane	69	Phophenyane	117
Ngweti	28	Hlatjiwe	70	Vissprui	118
Nkwakwa	29	Gwini	71	Mbuzulwane	119
Queens	30	Ndubazi	72	Kruisfonteinspruit	120
Motitsi	31	Mitomeni	74	Goudstroom	121
Houtbosloop	32	Waarkraalloop	75	Gemsbokspruit	122
Mzinti	33	Muhlambamadubo	76	Beestekraalspruit	125
Buffelskloofspruit	34	Sandspruit	77	Ndlobesuthu	126
Buffelskloofspruit	35	Lubyelubye	78	129, 130, 131,	
Mhlambanyatsi	36	Mosehla	82	132, 139,140,	
Musutlu	37	Lupelule	83	141	

* according to the 1:50 000 topographic map sheets both REACHNUMs 9 and 10 are called Mutlumuvi -in the case of REACHNUM 9 it is also the main upstream tributary of the Sand River

5.4 Visual Comparison

Appendix B presents plots of the 109 river main stem profiles used in the final analysis. Each plot shows the profile derived from 1:50 000 contours and river main stems, along with profiles derived by overlaying the 1:50 000 river lines with DEM20, DEM90 and DEM200.

The advantage of a visual comparison of the river longitudinal profiles derived from the four sources is that it is possible to immediately identify large anomalies between the datasets. A visual comparison, therefore, prepares the way for more detailed investigations by highlighting potential issues. Figure 5.3 shows the profiles for REACHNUMs 57, 60 and 104 derived from the 1:50 000 contours and river lines in comparison to those derived from the 20m, 90m and 200m DEMs.

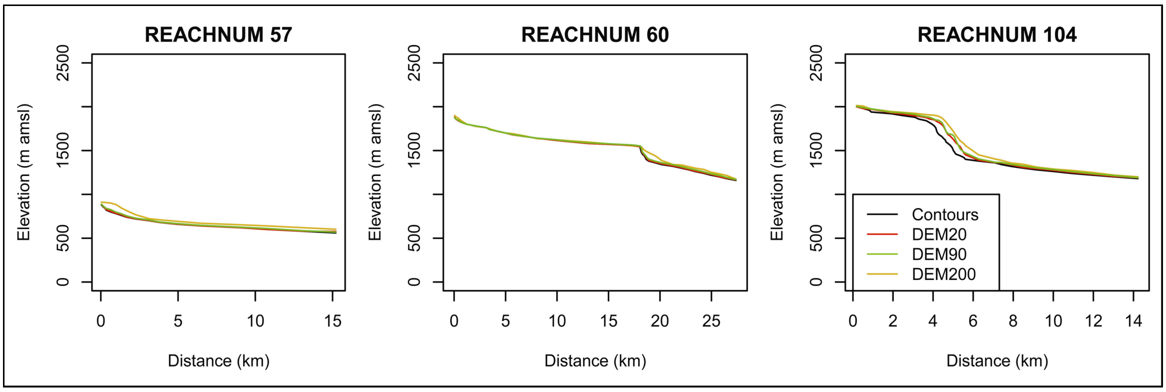


Figure 5.3: A comparison of three river profiles based on elevations derived from contours, DEM20, DEM90 and DEM200

In all three examples the yellow line i.e. the profile derived from DEM200, is visibly different to the other profiles in steep sections, where Digital Elevation Model resolution is too coarse to pick up the rapid change in elevation occurring within the 200m of the grid cell. For similar reasons both DEM20 and DEM90 diverge from the contour profile in the steep section of REACHNUM 104, with DEM200, however, showing the largest difference.

5.5 Scenario 1: Comparison to 1:50 000 contour line intersections

Table 5.3 illustrates the first ten distance and contour line elevation values derived from 1:50 000 topographic maps for the Crocodile River (REACHNUM 1). Using the interpolation techniques described earlier in Chapter 4 matching elevations are derived at the same distances along the profiles based on DEM20, DEM90 and DEM200. Given the distance and elevation values, slopes can be calculated for each 1:50 000 main stem section based on contour elevations as well as the three DEM derived elevation sets. These elevation and slope values are also included in Table 5.3. There will always be one less slope value than the number of elevation values per river.

Table 5.3: A comparison of ten distance and elevation values measured from 1:50 000 maps, DEM20, DEM90 and DEM200 (REACHNUM 1: Crocodile River)

1:50 000 Distance	1:50 000 Contour line		DEM20		DEM90		DEM200	
(m) from source	Height (m)	Slope (%)	Elev (m)	Slope (%)	Elev (m)	Slope (%)	Elev (m)	Slope (%)
168.6	2160		2162.7		2172.4		2189.3	
439.1	2140	7.4	2141.6	7.8	2153.4	7	2178.8	3.9
735.7	2120	6.7	2121.1	6.9	2123.2	10.2	2146.0	11.1
1344.0	2100	3.2	2100.5	3.4	2103.9	3.2	2115.9	4.9
2230.7	2080	2.3	2080.0	2.3	2087.2	1.9	2095.7	2.3
2932.3	2060	2.9	2060.5	2.8	2063.7	3.3	2074.2	3.1
3764.2	2040	2.4	2040.7	2.4	2043.3	2.5	2057.5	2
5250.5	2020	1.3	2019.8	1.4	2025.1	1.29	2026.1	2.1
6980.5	2000	1.2	1999.4	1.2	2004.0	1.2	2008.4	1
9141.4	1980	0.9	1980.3	0.9	1990.2	0.7	1988.9	0.9

5.5.1 Elevation

Distance and associated elevation values are calculated for 109 rivers in the X catchment, based on the points on the derived profile where the 1:50 000 contours intersect the 1:50 000 river main stem lines.

The non-parametric Mann-Whitney-Wilcoxon test (Snedecor and Cochran, 1980) is chosen to compare the elevations derived from the contour lines to those interpolated at the same distance from the profiles generated from DEM20, DEM90 and DEM200. The full list of results for these comparisons is in Appendix D.

The p-value derived from the statistical analysis is used to assess the significance of the similarity between the two data sets. The null hypothesis being tested is that there is no significant difference in distribution between the profiles and that the elevations of the DEM-derived profile are not significantly higher or lower than the contour-derived profile. A p-value of 0.05 is used as a confidence cut-off between accepting, or rejecting, this hypothesis. A p-value of less than 0.05 suggests that differences in elevation can be assumed to be significant at a 95% level of confidence.

Table 5.4 presents the percentage of rivers that show no significant difference between contour-based and DEM-derived elevations in the profile, with p-values greater than 0.05. The majority of longitudinal profiles show a significant difference in elevations between the heights based on 1:50 000 contour lines and those derived from the three DEMs. Closer examination of the test results revealed that in most cases the DEM-derived elevations are significantly higher than the contour-based elevations (Table 5.4).

Table 5.4: A summary of Mann-Whitney-Wilcoxon test results comparing 1:50 000 contour heights with DEM20, DEM90 and DEM200 elevations: % and number of profiles

Contour Height *vs:*	**DEM20**	**DEM90**	**DEM200**
No significant difference	35% (38)	20% (22)	14% (15)
Contours significantly higher	22% (24)	0% (0)	0% (0)
DEM significantly higher	43% (47)	80% (87)	86% (94)

However, each DEM has a vertical accuracy attached to it, and, although elevation differences between the contour heights and DEM elevations initially appear large, they cannot be evaluated without also considering the vertical accuracy of the DEM in question. DEM20 is listed as having an expected vertical accuracy of 6.8m, DEM90 a calculated vertical accuracy of 5m-16m and DEM200, 10m (see Chapter 4). Using the expected vertical accuracies as a basis, the absolute mean differences in elevation are allocated to seven classes:
<5m, 5m-10m, 10m-15m, 15m-20m, 20m-30m, 30m-50m and >50m.
Based on these classes, Figure 5.4 shows the distribution of the mean of the absolute differences between the contour and DEM elevations for each profile. According to these:

- 85% (93) of the 109 profile elevations extracted from DEM20 have an absolute mean difference within 5m of the contour line heights and 95% (104) of the profiles have an absolute mean difference within 10m of the contour line heights. One profile has an absolute mean difference greater than 50m (REACHNUM 104).
- 35% (38) of the 109 profile elevations extracted from DEM90 have an absolute mean difference within 5m of the contour line heights, 63% (69) of the profiles have an absolute mean difference within 10m, 79% (86) of the profiles have an absolute mean difference within 15m, and 92% (100) have an absolute mean difference within 20m of the contour line heights. Again, REACHNUM 104 is the only profile to have an absolute mean difference greater than 50m. Two profiles (REACHNUM 31 and REACHNUM 132) have an absolute mean difference between 30m and 50m.
- 13% (14) of the 109 profile elevations extracted from DEM200 have an absolute mean difference within 5m of the contour line heights and 57% (62) of the profiles have an absolute mean difference within 20m of the contour line heights. Twelve profiles have an absolute mean difference in the 50m-100m

range and one has an absolute mean difference of over 100m (REACHNUM 104).

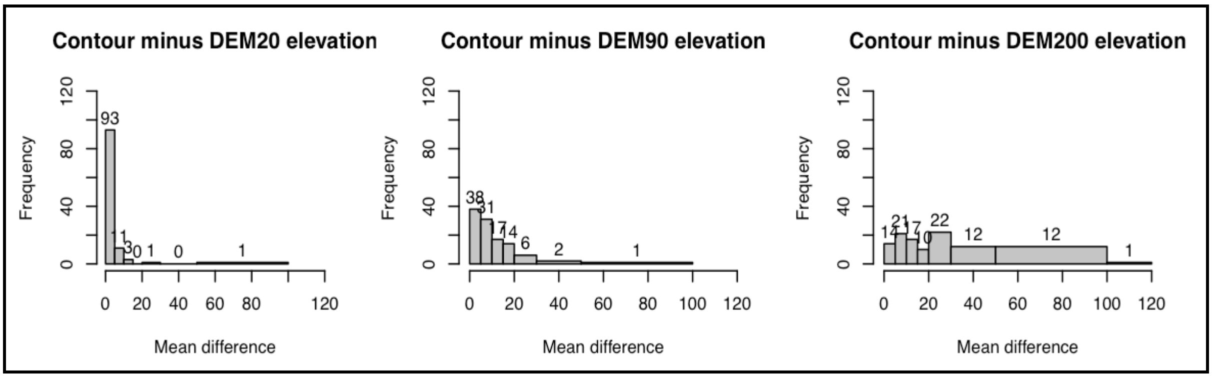


Figure 5.4: The distribution of absolute mean elevation differences when comparing 1:50 000 contour heights with DEM20, DEM90 and DEM200 elevations

The actual differences are plotted as line graphs above each profile in Appendix B and the absolute mean differences per profile are listed as a table in Appendix C. In all cases the profile of REACHNUM 104 (Gemakstroom) has the highest absolute mean difference when compared to contour elevations, caused by the discrepancy in profiles at the steep section of the river where DEM resolution is too course to accurately follow the nearly overlapping contour lines. The visual comparison undertaken in section 5.4 of this chapter also identified REACHNUM 104 as having a visible discrepancy between the DEM and contour derived profiles (Figure 5.5). The profiles of REACHNUM 31 and REACHNUM 132 also have steep sections showing a visible difference between the contour-and DEM- derived profiles and fall in the top two mean difference classes shown in Figure 5.4.

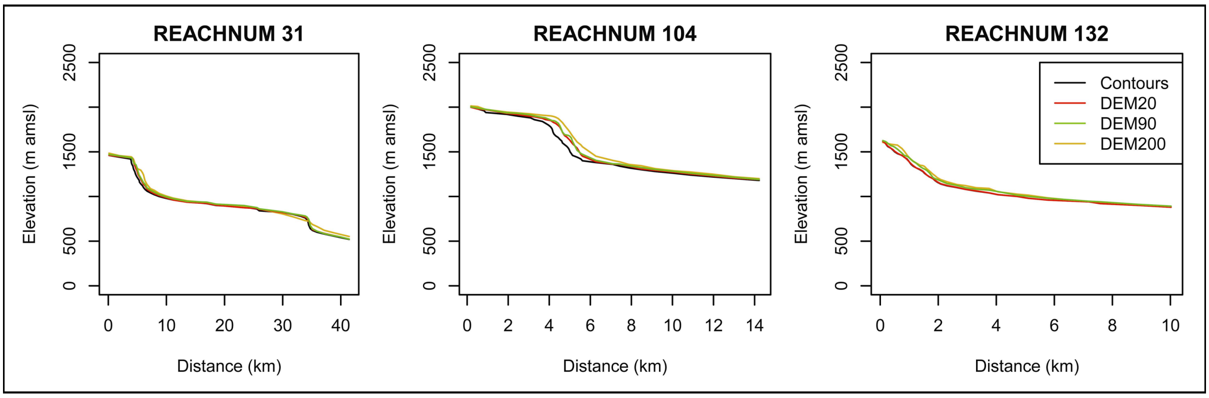


Figure 5.5: Contour line heights *vs* DEM20, DEM90 and DEM200 profiles for REACHNUMs 104, 31, and 132

5.5.2 Slope

The slope of the river line section between each river line/contour line intersection is calculated based on the elevation and distance values. The distance interval for the slope calculation is based on the 1:50 000 river line section length, while the start and end elevation for each section is derived from one of the four input datasets: contour lines, DEM20, DEM90 or DEM200.

Slopes are calculated for 109 river main stems. The slope for each 1:50 000 river line section between contours is compared to the same section using elevations derived from DEM20, DEM90 and DEM200. As an example, Table 5.3 above also lists slopes calculated for the first 10 sections along the Crocodile River (REACHNUM 1).

The Mann-Whitney-Wilcoxon test is used to evaluate the extent of similarity between the contour and DEM –derived slopes per segment. Table 5.5 presents a summary of these results. The full results for each profile are presented in Appendix E. A p-value greater than 0.05 indicates no significant difference between slopes at the 95% level. At all the DEM resolutions, more than 90% of the profiles show no significant difference between the contour line-based and DEM-derived slopes. In a small number of profiles the results suggest that the contour line-based slopes are steeper than slopes from the DEM-based profiles. In no profiles are the slopes from the DEM-derived profiles significantly steeper than the slopes of the contour line-based profiles.

Table 5.5: A summary of the Mann-Whitney-Wilcoxon test results comparing 1:50 000 contour slope sections with DEM20, DEM90 and DEM200 slopes: % and number of profiles

Contour Slope *vs:*	**DEM20**	**DEM90**	**DEM200**
No significant difference	99% (108)	98% (107)	93% (101)
Contours significantly steeper	1% (1)	2% (2)	7% (8)
DEM significantly steeper	0	0	0

The comparison of contour line section slopes and DEM200 has the fewest number of profiles (101) showing no significant difference between the profiles. Table 5.6 provides a summary of the profile numbers (REACHNUM) showing a significant difference between slopes. REACHNUM 104 is among these in the DEM20 and DEM90 comparisons.

Table 5.6: A summary of the profile REACHNUMs showing a significant difference comparing 1:50 000 contour slope sections with DEM20, DEM90 and DEM200 slopes

Contour Slope *vs:*	**DEM20**	**DEM90**	**DEM200**
			54
		62	62
			68
	104	104	
			105
			113
			117
			139
			141

Closer examination of the instances showing a significant difference between the contour line-based slopes and slopes based on DEM elevations, revealed in all cases steep sections in the profile, with a contour spacing less than the DEM resolution and the DEM resolution thus not being sufficient to resolve the steep change in elevation illustrated by the close contour spacing. Digital Elevation Model resolution appears to be the main factor affecting the differences in the slopes derived along the profiles.

Figure 5.6 shows the differences in slope between the contour-derived profile and the DEM-derived slopes plotted against the contour slopes. The values for all 109 main stem profiles in the X catchment, at each resolution, have been combined for the purposes of these plots. Each plot illustrates the distribution of differences against contour slope, with differences being calculated as DEM-slope minus contour slope. As the contour slope increases these differences become larger in a negative direction, revealing that the DEM-derived slopes tend to underestimate the contour slopes. Furthermore, the largest differences are observed where contour slopes are highest.

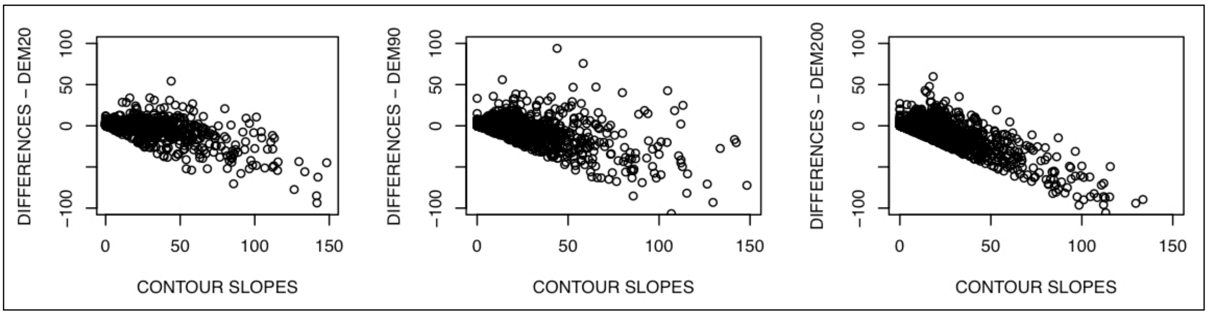


Figure 5.6: Contour-derived slope *vs* differences in slope (DEM-slope - contour-slope) (all slopes shown as %)

5.6 Scenario 2: Comparison of profiles interpolated at equal horizontal distance intervals

In the second set of comparisons, each of the 109 river main stem profiles is divided into equal distance intervals, with the main stem source being distance 0. Five intervals of increasing horizontal distance are used: 100m, 200m, 300m, 400m and 500m. Elevation values are interpolated directly from the text files of elevations derived from 1:50 000 contour line intersections, DEM20, DEM90 and DEM200. Slopes are calculated based on the horizontal distance and elevation values for each profile. In Figure 5.7 REACHNUM 139 is used as an example to show the horizontal intervals used along each river main stem profile.

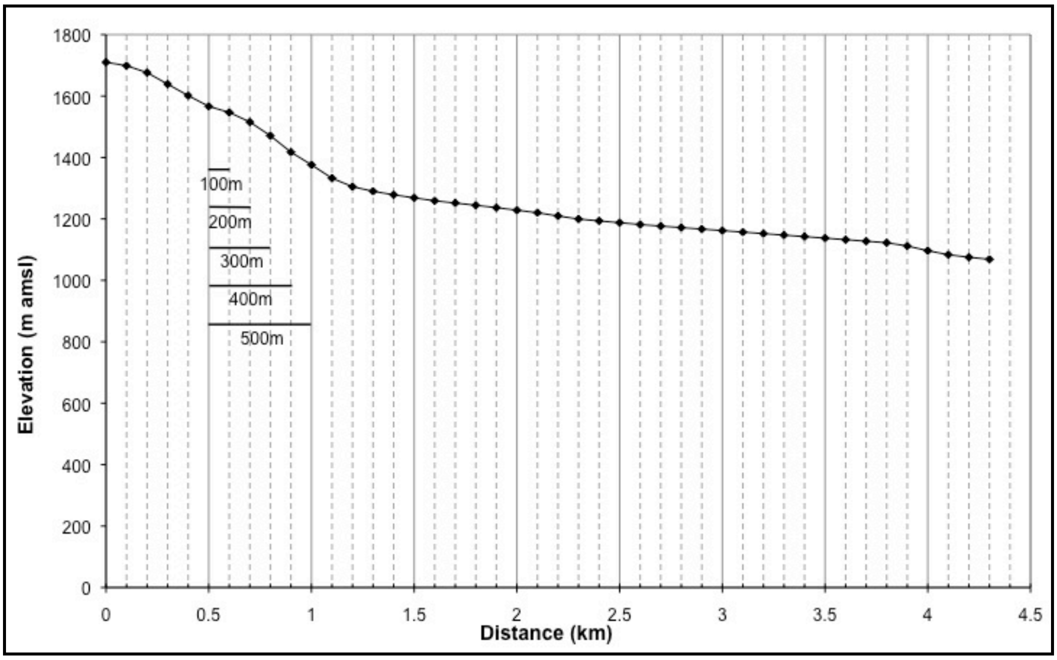


Figure 5.7: 100m to 500m horizontal intervals along a main stem profile (REACHNUM 139)

5.6.1 Elevation

The Mann-Whitney-Wilcoxon test is used to statistically compare the elevations derived for each set of horizontal distance intervals. The full list of results for profiles based on 100m, 200m, 300m, 400m and 500m horizontal intervals are presented in Appendices F to J. A p-value greater than 0.05 indicates no significant difference between slopes at the 95% level.

Table 5.7 summarises the number of profiles that show no significant difference in elevations between contour line-derived and DEM-derived elevations for each horizontal distance interval. In most cases less than 10% of the profiles compared show no significant difference between elevations. Closer examination of the results revealed that in most cases the DEM-derived elevations are significantly higher than the elevations based on 1:50 000 contour lines (summarised in Table 5.7).

However, the profiles should be compared by taking into consideration the expected vertical accuracy of each DEM. Figure 5.8 shows the frequency of absolute mean difference values for each contour profile / horizontal interval comparison, in seven classes: <5m, 5m-10m, 10m-15m, 15m-20m, 20m-30m, 30m-50m and >50m. It was found that the mean difference in elevation between the profiles is very similar for all five horizontal comparisons per DEM. This is because the same base profile is used to interpolate the horizontal intervals. The 100m interval is the profile on which the other interval profiles are based. The frequency of absolute mean differences between the 100m profile and the contour profile, therefore, is used in Figure 5.8 to represent all horizontal profile intervals.

Table 5.7: A summary of the Mann-Whitney-Wilcoxon test results when comparing 1:50 000 contour profile elevations at 100m-500m intervals with DEM20, DEM90 and DEM200 elevations: % and number of profiles

Contour Height *vs:*			**DEM20**		
	100m	**200m**	**300m**	**400m**	**500m**
No significant difference	8% (9)	8% (9)	11% (12)	14% (15)	16% (17)
Contours significantly higher	5% (6)	5% (6)	5% (6)	5% (5)	5% (5)
DEM significantly higher	86% (94)	86% (94)	83% (91)	81% (89)	79% (87)
Contour Height *vs:*			**DEM90**		
	100m	**200m**	**300m**	**400m**	**500m**
No significant difference	4% (4)	6% (6)	7% (8)	8% (9)	7% (8)
Contours significantly higher	5% (6)	7% (8)	5% (5)	5% (5)	5% (5)
DEM significantly higher	91% (99)	87% (95)	88% (96)	87% (95)	88% (96)
Contour Height *vs:*			**DEM200**		
	100m	**200m**	**300m**	**400m**	**500m**
No significant difference	3% (3)	6% (6)	5% (5)	5% (5)	6% (6)
Contours significantly higher	2% (2)	1% (1)	2% (2)	2% (2)	9% (1)
DEM significantly higher	95% (104)	93% (102)	93% (102)	93% (102)	93% (102)

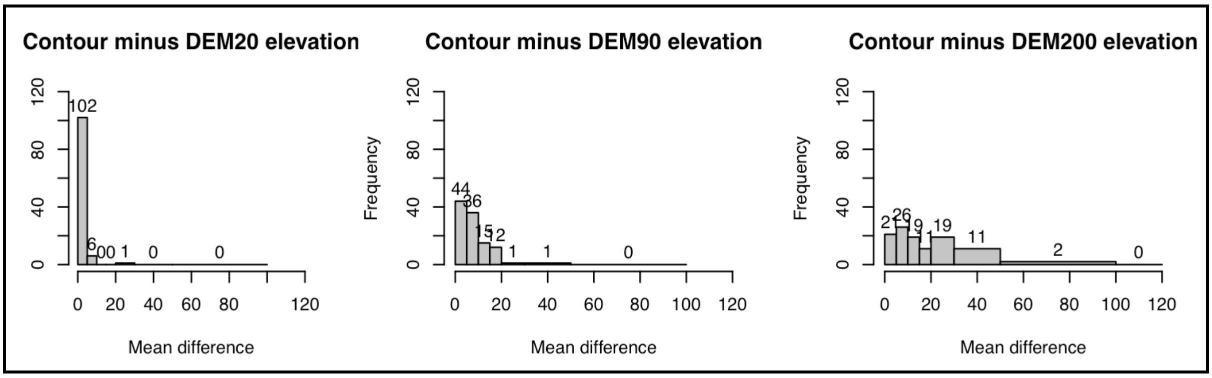


Figure 5.8: Distribution of mean elevation differences when comparing 1:50 000 contour heights with equal horizontal intervals for DEM20, DEM90 and DEM200 elevations

According to the frequency distributions in Figure 5.8:

- 94% (102) equal interval profiles derived from DEM20 have an absolute mean difference less than 5m from the contour line-based profile elevations at the same horizontal elevation and 99% (108) profiles have an absolute mean difference less than 10m. Only one profile exceeds 20m – in this case, REACHNUM 104

- 87% (95) equal interval profiles derived from DEM90 have an absolute mean difference less than 15m from the contour line-based profile elevations at the same horizontal elevation. Two profiles exceed 20m absolute mean difference: REACHNUM 104 and REACHNUM 132
- 43% (47) equal interval profiles derived from DEM200 have an absolute mean difference less than 10m from the contour line-based profile elevations at the same horizontal elevation. Two profiles exceed 50m absolute mean difference: REACHNUM 104 and REACHNUM 125.

When comparing elevations derived at equal horizontal intervals based on the three DEMs to elevations at the same distances on the contour line-based profiles, REACHNUM 104 (Figure 5.9) has an absolute mean difference in the highest range for all DEMs. Examining the profiles for REACHNUM 104 and REACHNUMs 125 and 132 (Figure 5.9) illustrate the visible differences in the steep sections where the DEM and contour line-based profiles differ.

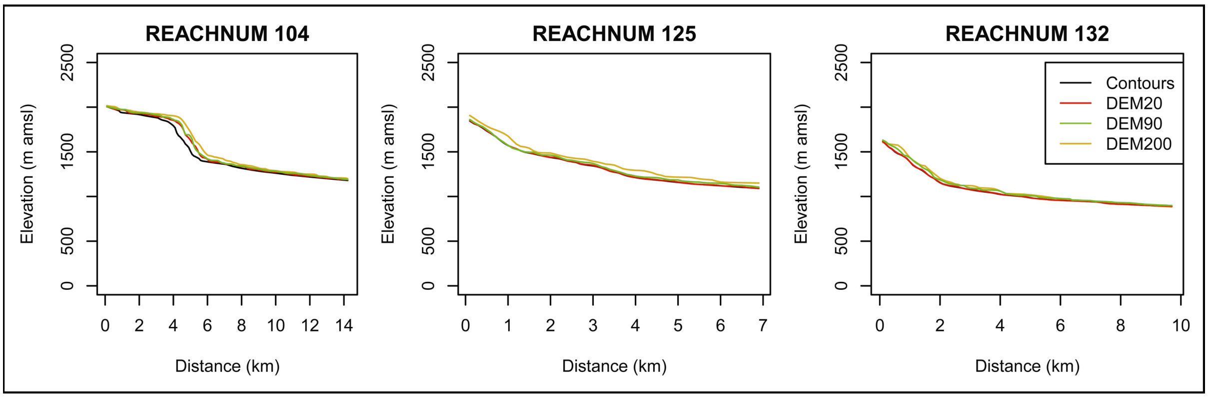


Figure 5.9: Contour vs DEM20, DEM90 and DEM200 profiles for REACHNUM 104, 125, and 132 derived at 100m horizontal intervals

5.6.2 Slope

The Mann-Whitney-Wilcoxon test is used to statistically compare the slopes derived for each set of horizontal distance intervals. Table 5.8 presents the number of profiles that show no significant difference between contour line-derived and DEM derived slopes for each horizontal distance interval. The full list of results for these comparisons at 100m, 200m, 300m, 400m and 500m intervals are presented in Appendices K - O. A p-value greater than 0.05 indicates no significant difference between slopes at the 95% level.

The 100m horizontal distance interval has the lowest number of significantly comparable profiles. As the horizontal distance at which slopes are calculated, increases, so the number of profiles showing no significant difference between contour line-based slopes and slopes based on DEM-derived elevations, also increases. At 200m horizontal distance intervals more than 80% of the slopes calculated using elevations from the 90m DEM show no significant difference between the contour and DEM based slopes. At 400m horizontal distance intervals more than 80% of the profiles at all DEM resolutions show no significant difference in slopes, with neither the contour-based or DEM- based profiles having significantly steeper slopes.

In all cases DEM90 had the highest number of profiles showing no significant difference between the 1:50 000 river line-based profiles and the 1:500 000 river line-based profiles.

In almost all cases where there is a significant difference between the contour and DEM –based slopes, the contour line-based slopes are steeper than the slopes derived from the DEM-based profiles.

Table 5.8: A summary of the Mann-Whitney-Wilcoxon test results when comparing 1:50 000 contour line-based profile slopes at 100m-500m intervals with DEM20, DEM90 and DEM200 –derived slopes: % and number of profiles

Contour Height *vs:*	**DEM20**				
	100m	**200m**	**300m**	**400m**	**500m**
No significant difference	40% (44)	60% (65)	78% (85)	86% (94)	91% (99)
Contours significantly steeper	60% (65)	40% (44)	22% (24)	14% (15)	9% (10)
DEM significantly steeper	0	0	0	0	0
Contour Height *vs:*	**DEM90**				
	100m	**200m**	**300m**	**400m**	**500m**
No significant difference	54% (59)	82% (89)	93% (101)	97% (106)	99% (108)
Contours significantly steeper	46% (50)	18% (20)	7% (8)	3% (3)	1% (1)
DEM significantly steeper	0	0	0	0	0
Contour Height *vs:*	**DEM200**				
	100m	**200m**	**300m**	**400m**	**500m**
No significant difference	44% (48)	72% (78)	86% (94)	90% (98)	94% (103)
Contours significantly steeper	55% (60)	28% (31)	14% (15)	9% (10)	5% (5)
DEM significantly steeper	1% (1)	0	0	1% (1)	1% (1)

Closer examination of the individual profiles revealed that the standard deviation of the profile slopes decreases as horizontal interval increases. Table 5.9 shows the number of profiles, calculated at each consecutive horizontal interval, which have a standard deviation less than the standard deviation of the 100m profile. At 200m horizontal steps, 46 of the 1:50 000 contour-derived profiles have a lower standard deviation than the same profiles split into 100m horizontal steps. However, at 500m intervals 84 contour-derived profiles have a lower standard deviation than the same profiles split into 100m horizontal steps. Similarly, at 200m intervals 53, 56 and 63 of the DEM20, DEM90 and DEM200 -derived profiles, respectively, have a standard deviation lower than the same profile divided into 100m intervals. At 500m intervals 103, 103 and 107 of the DEM20, DEM90 and DEM200 -derived profiles, respectively, have a standard deviation lower than the same profile divided into 100m intervals.

Table 5.9: A summary of the number of profiles with a lower standard deviation than the 100m profile, per horizontal interval

Source	**Horizontal interval**			
	200m	300m	400m	500m
Contour	46	76	95	84
DEM20	53	100	94	103
DEM90	56	102	102	103
DEM200	63	102	104	107

This decrease in variability as horizontal interval increases is also evidenced in the plots in Figure 5.10 where the differences between contour line-derived slopes and DEM-derived slopes are plotted against original contour line-derived slopes. Differences are calculated as DEM-derived slope minus contour-derived slope, at each corresponding horizontal interval measurement. As horizontal interval increases the underestimation by DEM-derived slopes becomes less. This is most noticed when examining the higher contour slopes where differences are larger at smaller horizontal intervals.

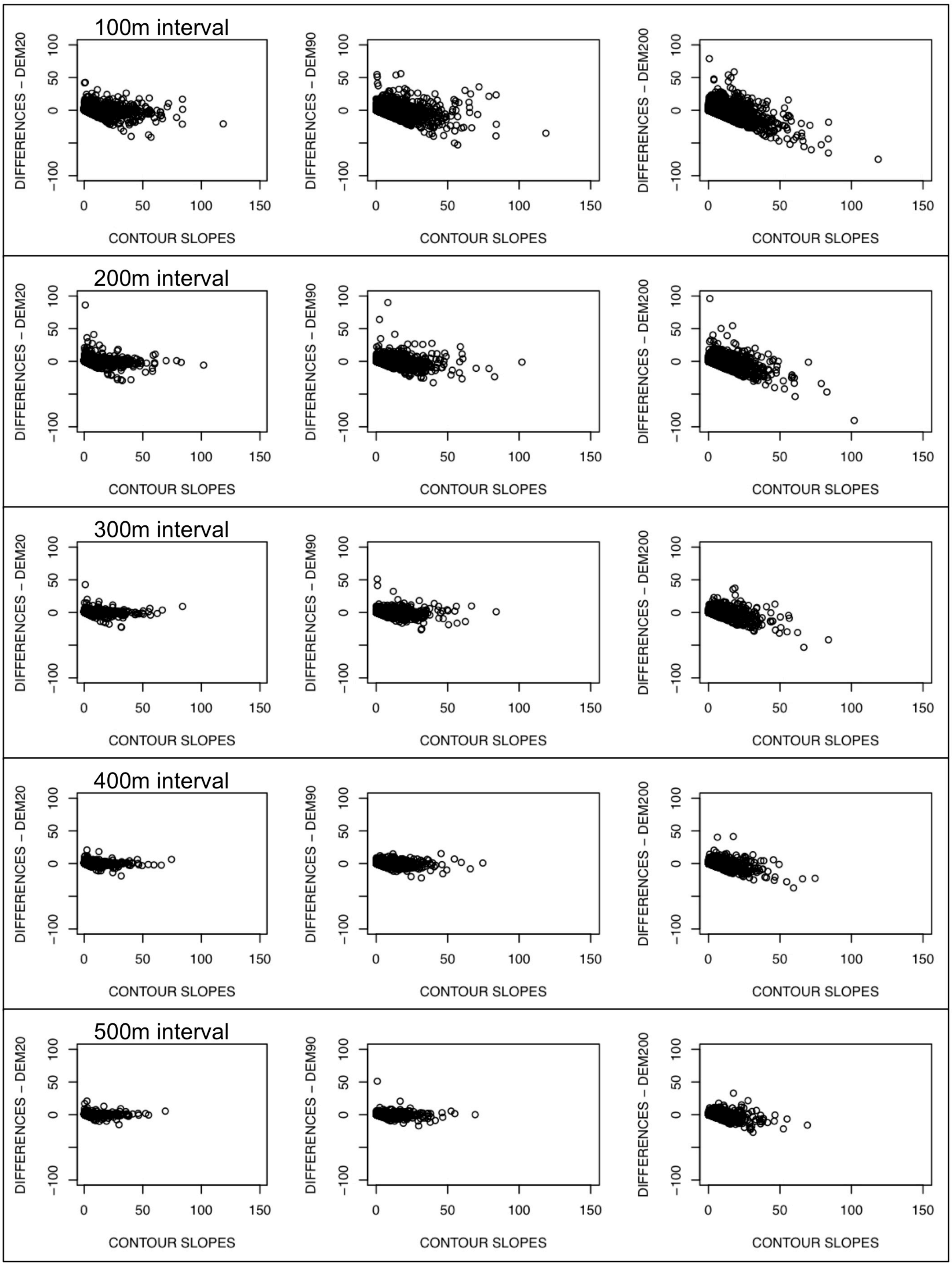


Figure 5.10: Contour-derived slope *vs* differences in slope (DEM-slope - contour-slope) measured at increasing horizontal intervals (all slopes shown as %)

5.7 Summary

The comparisons between the contour-generated profiles and the DEM-generated profiles can be divided into two broad sections: comparison of elevations and slopes at horizontal intervals based on the horizontal contour spacing on the 1:50 000 map sheets; and comparison of elevations and slopes based on equal horizontal distances ranging from 100m to 500m at 100m intervals.

- **Elevations** based on contour intervals and equal horizontal intervals

  The statistical comparisons based on the Mann-Whitney-Wilcoxon test show that there is a significant difference in elevations between the contour line-based and DEM–derived elevations based on both contour intervals and equal horizontal intervals. In almost all cases the DEM-derived elevations are significantly higher than the 1:50 000 contour line elevations.

  However, a comparison of absolute mean differences in elevation between contour and DEM profiles indicates that, in all cases, more than 85% of profiles derived from DEM20 and 79% derived from DEM90 have an absolute mean difference in elevation within the vertical accuracy of the DEM being compared (Table 5.10). Fewer than 35% of profiles derived from DEM200 have an absolute mean difference within the vertical accuracy of the DEM.

  Table 5.10: Percent of absolute mean difference between contour-based elevations and DEM-derived elevations, with respect to expected DEM vertical accuracy (*va*)

Contour Intervals	DEM20 *(va = 6.8m)*	DEM90 *(va = 16m)*	DEM200 *(va = 10m)*
5m	85%	35%	13%
10m	95%	63%	32%
15m	98%	79%	48%
Equal Horizontal Intervals			
5m	94%	43%	23%
10m	99%	75%	47%
15m	99%	87%	61%

- **Slopes** based on contour intervals and equal horizontal intervals

  Conversely, the results of the Mann-Whitney-Wilcoxon test comparing slopes between 1:50 000 contour-based profiles and DEM-derived profiles indicate that more than 90% of profiles show no significant difference in derived slopes (Table 5.11). In the few cases where a significant difference between slopes is observed, the contour-based slopes are steeper.

In the case of profiles compared at equal horizontal intervals, more than 90% of profiles for all comparisons for DEM20, DEM90 and DEM200 show no significant difference in derived slopes at 500m distance intervals. However, as horizontal distance decreases the number of profiles with a significant difference between slopes, also decreases. At 100m intervals only DEM90 has more than 50% profiles that can be said to have slopes that are significantly similar to the contour-derived slope values. At all horizontal distances DEM90 had the highest number of profiles showing no significant difference between the 1:50 000 river line-based profiles and the 1:500 000 river line-based profiles. In almost all cases where a significant difference in slopes is observed, the slopes based on 1:50 000 scanned contour lines are steeper.

Table 5.11: Percent of profiles showing no significant difference between derived slopes

Contour Intervals	DEM20	DEM90	DEM200
	99%	98%	93%
Equal Horizontal Intervals			
100m	40%	54%	44%
200m	60%	82%	72%
300m	78%	93%	86%
400m	86%	97%	90%
500m	91%	99%	94%

These results, together with any recommendations arising from them, are discussed further in Chapter 6**.**

CHAPTER 6
CONCLUSIONS

6.1 Introduction

This study investigates the use of Digital Elevation Models to derive river longitudinal channel slope based on a methodology designed to automate the process so that assessments can be undertaken at various scales ranging from local to national, while retaining the integrity of river naming and hierarchy within a catchment. The main findings are centered around a comparison between elevations and slopes derived from 20m, 90m and 200m resolution Digital Elevation Models, and those extracted from contour lines scanned off 1:50 000 topographic map sheets. The X primary catchment situated in the eastern regions of South Africa and incorporating the Sabie and Crocodile Rivers, is chosen as a study area to carry out the comparisons.

6.2 Summary of methodology

Comparisons are formed around two reference scenarios. The first establishes a set of reference longitudinal river profiles based on the river lines from scanned and vectorised 1:50 000 map sheets. To create the profiles elevations are extracted at the intersections of these river lines with 1:50 000 scanned contour lines. The second reference scenario uses these same derived longitudinal profiles, but divided into five sets of equal horizontal intervals: 100m, 200m, 300m, 400m and 500m.

The test profiles to be compared to the reference profiles are based on river lines originally scanned and vectorised from 1:500 000 map sheets, but adjusted to be within 50m of the location of 1:50 000 river lines (DWAF, 2006). These river lines are combined using an automated procedure to form single lines representing the existing rivers in the catchment. At 1:500 000 scale 143 such 'main stems' are identified in the X catchment. A second automated procedure is applied to extract elevations along these main stems from DEMs at three resolutions (20m, 90m and 200m). Distances and their associated elevations along each main stem are automatically saved to a text file and can be used to draw longitudinal profiles. Elevations and slopes along these profiles are then compared to those of the reference 1:50 000 profiles according to the two scenarios referred to above.

According to the Shapiro-Wilk test neither the elevations nor the slopes are found to come from a normally distributed population. The non-parametric Mann-Whitney-Wilcoxon test is used to examine whether there are significant differences between the elevations and slopes of the compared profiles.

6.3 Summary of results

Scanned river lines representing 109 of the 143 main stems in primary catchment X are assessed. Twenty-two main stems are excluded because they overlap Swaziland, which is not included in the South African 1:50 000 contour lines data set nor in the 20m resolution DEM (DEM20). A further twelve main stems are excluded from the analysis on the basis of having fewer than five sampling points.

A visual comparison of 1:50 000 river and contour line -based profiles and the 1:500 000 river line and DEM-based profiles plotted together illustrates larger differences at sections of steep slopes, An examination of scatter-plots of the differences between contour-derived and DEM-derived slopes *vs* contour-derived slopes also illustrates larger differences at steep slopes.

The Mann-Whitney-Wilcoxon paired sample test is used to assess whether the elevations and slopes of the profiles derived by the various methods are significantly different. The DEM-derived elevations extracted at the same points as 1:50 000 stream/contour line intersections are significantly higher than the contour line-based heights, at the 95% confidence level. For both DEM90 and DEM200 derived profiles, more than 80% of the profiles compared had DEM elevations significantly higher than the contour line heights.

Similarly, elevations extracted at horizontal distance intervals of 100m to 500m along the profiles also show a significant difference. In more than 80% of the profiles, at all horizontal distances, the DEM-derived elevations are significantly higher than the contour-based elevations, at the 95% confidence level. DEM200 has the highest number of profiles showing a significant difference, with DEM-derived elevations being significantly higher than contour heights at more than 90% of the profiles compared.

However, when considering slopes based on these elevations, more than 90% of the profiles at all three DEM resolutions show no significant difference to slopes based on 1:50 000 river line / contour line intersections, at the 95% confidence level. Results for DEM20 and DEM90 show 99% and 98% of slopes, respectively, having no significant difference in derived slopes.

When considering slopes calculated from the elevations extracted at equal horizontal distances, also, it is found that the majority of slopes show no significant difference at the 95% confidence level. In all cases where a significant difference in slopes *is* observed, the contour-based slopes are steeper. It is also found that, as horizontal distance increases, the number of profiles showing significant differences in slopes decreases. At 300m intervals more than 70% of profiles show no significant difference between slopes. At 500m distance intervals more than 90% of the profiles at DEM20, DEM90 and DEM200 comparisons show no significant difference in derived slopes. At all horizontal distances DEM90 had the highest number of profiles showing no significant difference between the 1:50 000 river line-based profiles and the 1:500 000 river line-based profiles.

6.4 Conclusions

In summary, the following findings are pertinent to this study:

- even though contour-line based heights and those extracted from DEMs differ significantly, these differences appear less obvious when taking into consideration the vertical accuracy of each DEM,
- despite the significant differences observed between elevations, fewer profiles show significant differences in slopes derived from these elevations
- DEM-derived elevations tend to be significantly higher than contour line elevations
- however, where differences in slope do occur, contour line-derived slopes tend to be significantly steeper than DEM-derived slopes
- the number of profiles showing no significant difference in slopes increases as the horizontal distance between measurements increases
- larger differences are observed between contour-based and DEM-derived slopes at steep sections in the profiles
- DEM90 has the highest number of profiles showing no significant difference between slopes based on 1:50 000 contour line heights and slopes based on DEM-derived elevations

These results have relevance in answering the questions raised in the problem statement outlined at the beginning of the study. Based on these results listed above it can be said that when comparing slopes derived from 1:50 000 contour line elevations to those based on DEM elevations, steep slopes tend to be more underestimated by the DEM than flatter slopes. More than 90% of profiles based on contour intervals and more than 90% of slopes derived at 500m horizontal distance intervals show no significant difference between slopes.

The main question put forward in Chapter 1 to be answered by the study is: can river longitudinal profiles and slopes generated from a DEM and based on 1:500 000 mapped river lines adjusted to within 50m of 1:50 000 mapped river lines, be used as effectively as river longitudinal profiles extracted from 1:50 000 mapped contours and based on 1:50 000 mapped rivers lines? The findings of this study suggest that the adjusted 1:500 000 river lines available from DWA (DWAF, 2003; DWAF 2006) combined with elevations from medium to low resolution DEMs can be used as a substitute for 1:50 000 river line and contour line- based profiles. They also suggest that the automated GIS procedure used to extract and combine these values could be applied in other areas where the 1:500 000 river lines and medium to low resolution DEMs are available.

The research hypothesis that there is a significant difference between slopes derived from profiles based on the 1:50 000 rivers and contour line intersections and those derived from DEMs and 1:500 000 adjusted river lines, is rejected for profile slopes based on contour intervals and slopes derived at 500m horizontal distance intervals from all DEM resolutions. In terms of the individual DEMs the hypothesis is rejected for slopes derived at horizontal distances of 400m and more for DEM20, distances of 200m and more for DEM90, and distances of 300m and more for DEM200. This is based on more than 80% of profiles showing no significant difference in derived slopes. Therefore, the null hypothesis of no significant difference between slopes based on the two sources is accepted. It is therefore suggested that river longitudinal profiles and slopes generated from a DEM and based on 1:500 000 mapped river lines adjusted to within 50m of 1:50 000 mapped river lines, can be used as effectively as river longitudinal profiles extracted from 1:50 000 mapped contours and based on 1:50 000 mapped rivers lines.

6.5 Recommendations

Despite limitations, the longitudinal profile slopes derived from DEM90 have been shown to be adequate for river characterisation at a broad scale (Roux *et al*, 2008) and have been applied successfully at national scales (Dollar *et al*, 2006; Partridge *et al*, 2010). It is recommended that they can be considered reliable enough to be used as an initial assessment mechanism for the analysis of river physical characteristics at a medium to broad scale. It is not recommended that any data produced by this method from these DEMs be used for fine-scale hydrological or geomorphological analysis.

The more detailed 1:50 000 scanned river lines are being linked and attributed by DWA (Twynam, 2011) and will form a more detailed data source of river lines available nationally within the borders of South Africa. Weepener *et al* (2010) have produced a combined SRTM and ASTER 30m DEM for Southern Africa where 1:50 000 20m interval contour lines and the ASTER DEM are used to fill gaps in the latest 30m (1 arc-second) SRTM DEM. This DEM is available for the whole of South Africa and including the catchments extending beyond the borders of the country. A number of recommendations can be made, based on this information:

- It is recommendation is that the analysis be extended to a 30m resolution. It is suggested that the 1-arc-second (approx 30m) STRM DEM (Weepener *et al*, 2010) be considered to be used to produce a national layer of longitudinal profile slopes, based on the 1:50 000 rivers (when available) as being closer in scale to a 30m resolution DEM.
- Profiles based on the 1:50 000 scanned river lines can be calculated for river sections within the borders of South Africa and combined with the adjusted 1:500 000 river lines currently available from DWA to include sections outside the country's borders.

- Finally, it is recommended that emphasis be placed on ensuring that the 30m SRTM-based DEM being developed (Weepener, 2010) is hydrologically correct. The advantage of such a DEM is that river lines and elevations can be produced automatically, replacing the reliance on scanned river lines or contour lines from map sheets.

6.6 Summary

The semi-automated method and data sources described in this study are shown to have the potential to provide a national level dataset of preliminary river longitudinal slope values that can be used by specialists as a basis for further characterising river sections. Using this method it is possible to derive the required elevations and slopes in a manner that is rapid, repeatable and reliable, and avoids the potential of human error introduced when manually deriving slopes from a contour map. New developments in terms of the availability of input data sources at increased resolutions will make it possible to derive profiles and associated slopes at a more detailed level, extending the scope of desktop analyses.

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APPENDIX A

Manual procedure for the Mann-Whitney-Wilcoxon signed rank sum test based on matched pairs, for REACHNUM 113, comparing contour line and DEM200 based slopes (methodology based on Snedecor and Cochran, 1980)

Contour slope	DEM200 slope	Diffs (A)	Abs diffs (B)	Ordered (C)	Ranked (D)	Re-signed (E)
0.2441	0.0065	0.2376	0.2376	0.0001	1	-1
0.1381	0.0065	0.1316	0.1316	0.0004	2	2
0.1116	0.0065	0.1051	0.1051	0.0024	3	-3
0.0886	0.0451	0.0435	0.0435	0.0038	4	4
0.0591	0.0119	0.0472	0.0472	0.0039	5	5
0.0652	0.0981	-0.0329	0.0329	0.0170	6	6
0.0516	0.0346	0.0170	0.0170	0.0172	7	7
0.0388	0.0216	0.0172	0.0172	0.0329	8	-8
0.0206	0.0168	0.0038	0.0038	0.0435	9	9
0.0170	0.0194	-0.0024	0.0024	0.0472	10	10
0.0109	0.0069	0.0039	0.0039	0.1051	11	11
0.0099	0.0095	0.0004	0.0004	0.1316	12	12
0.0091	0.0091	-0.0001	0.0001	0.2376	13	13
Total sum of all ranks					91	
Total sum of positive ranks						79
Total sum of negative ranks (sign ignored) **(F)**						12

Where:

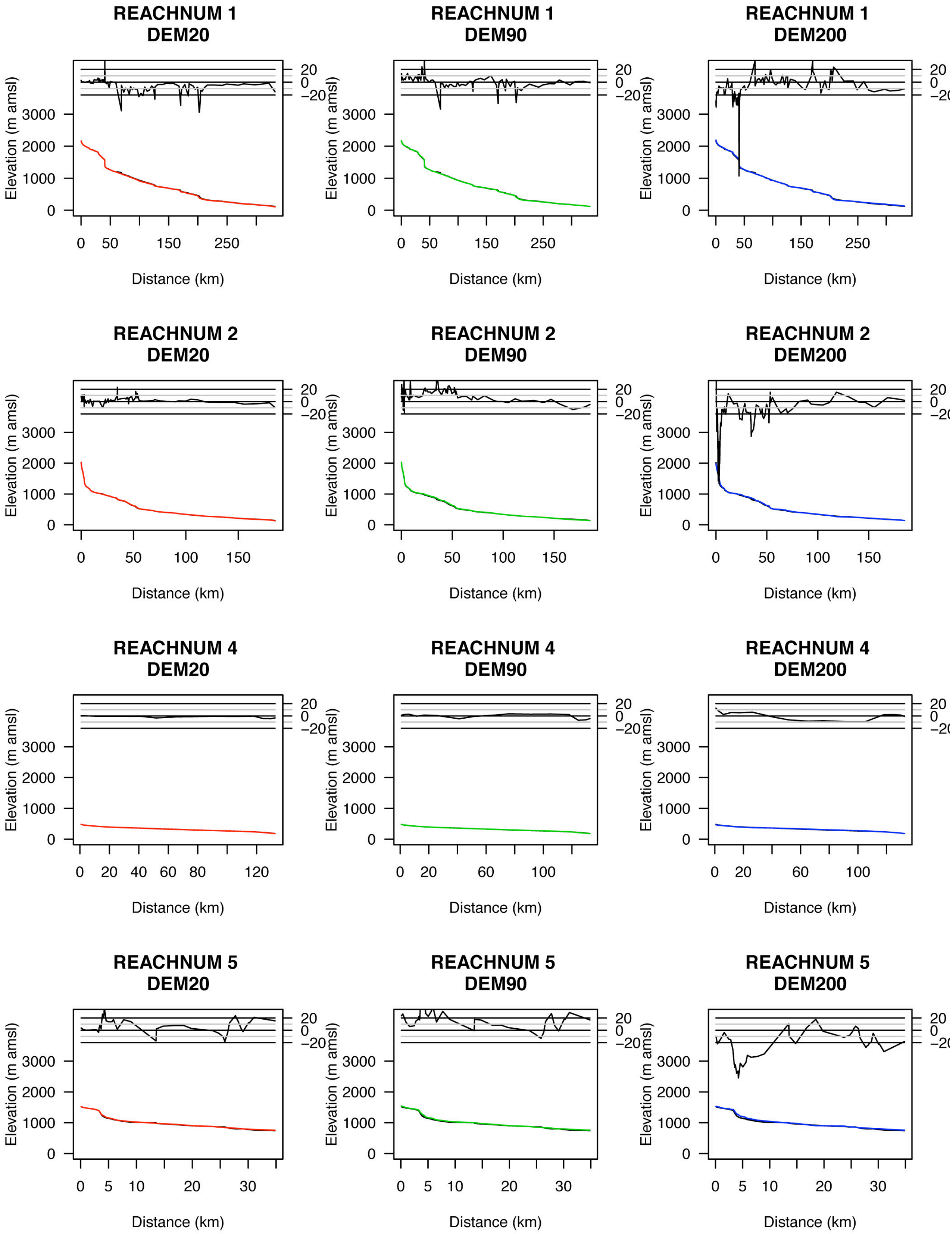
- **(A)** = contour slope minus DEM200 slope
- **(B)** the absolute value of (A) i.e. the absolute difference between each pair of values
- **(C)** the absolute differences sorted from lowest to highest
- **(D)** the absolute differences ranked from lowest to highest
- **(E)** the signs re-applied to the ranks to identify which originally came from positive or negative differences

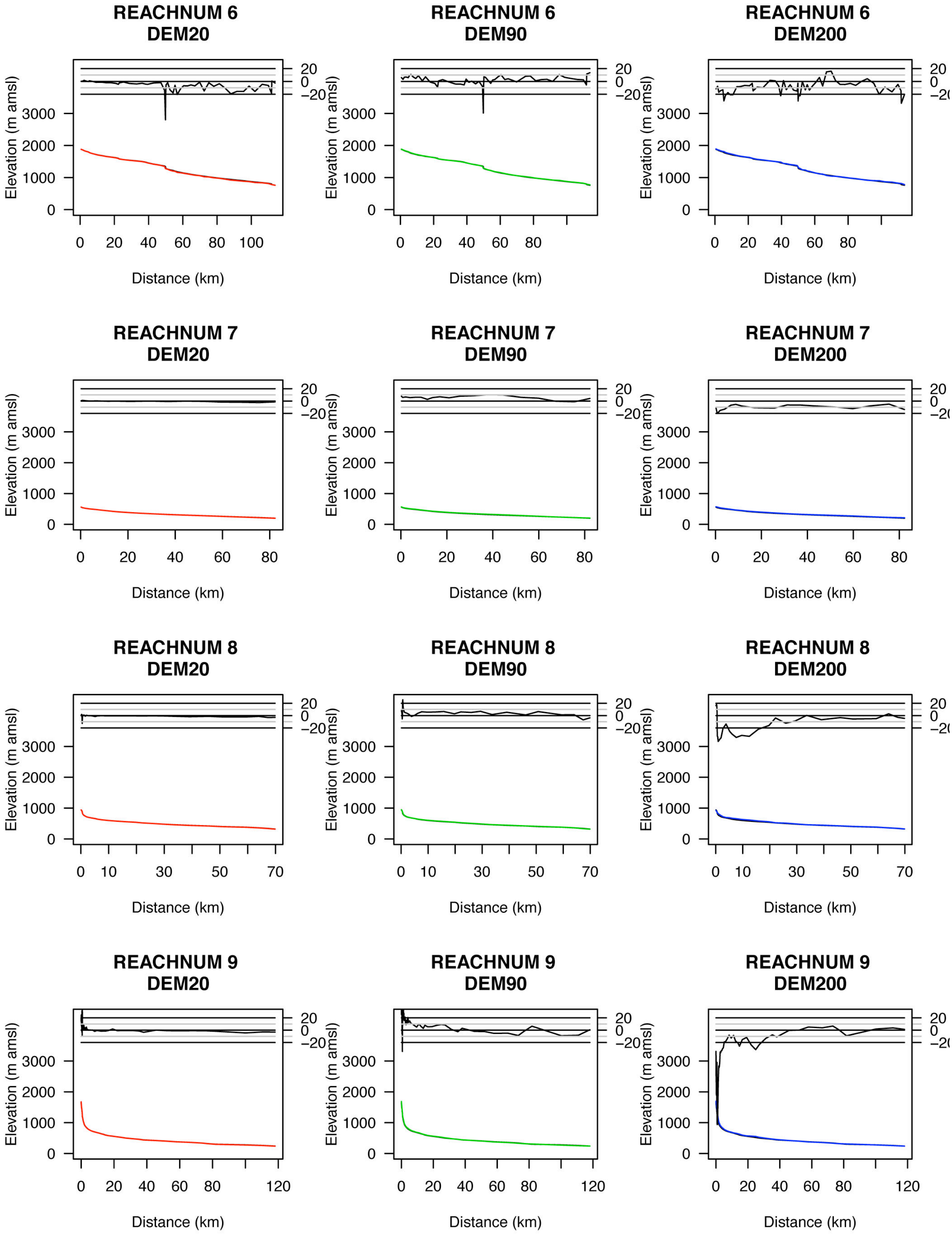
The smallest signed rank total is the test criterion for the Mann-Whitney-Wilcoxon signed rank sum test. This number is then compared to significance tables for the test such as those published in Snedecor and Cochran (1980). According to the published values in Snedecor and Cochran (1980), for a sample size of 13 pairs, a rank sum value less than 17 can be considered significant at the 5% level and would support rejection of the null hypothesis at the 5% level.

With a value of 12, the sum of negative ranks **(F)** is the smallest rank sum in this example. Since 12 is less than 17 it can be said that the contour-based slopes are significantly steeper than the DEM200 slopes – with significantly more positive that negative differences between the two.

APPENDIX B

River longitudinal profiles

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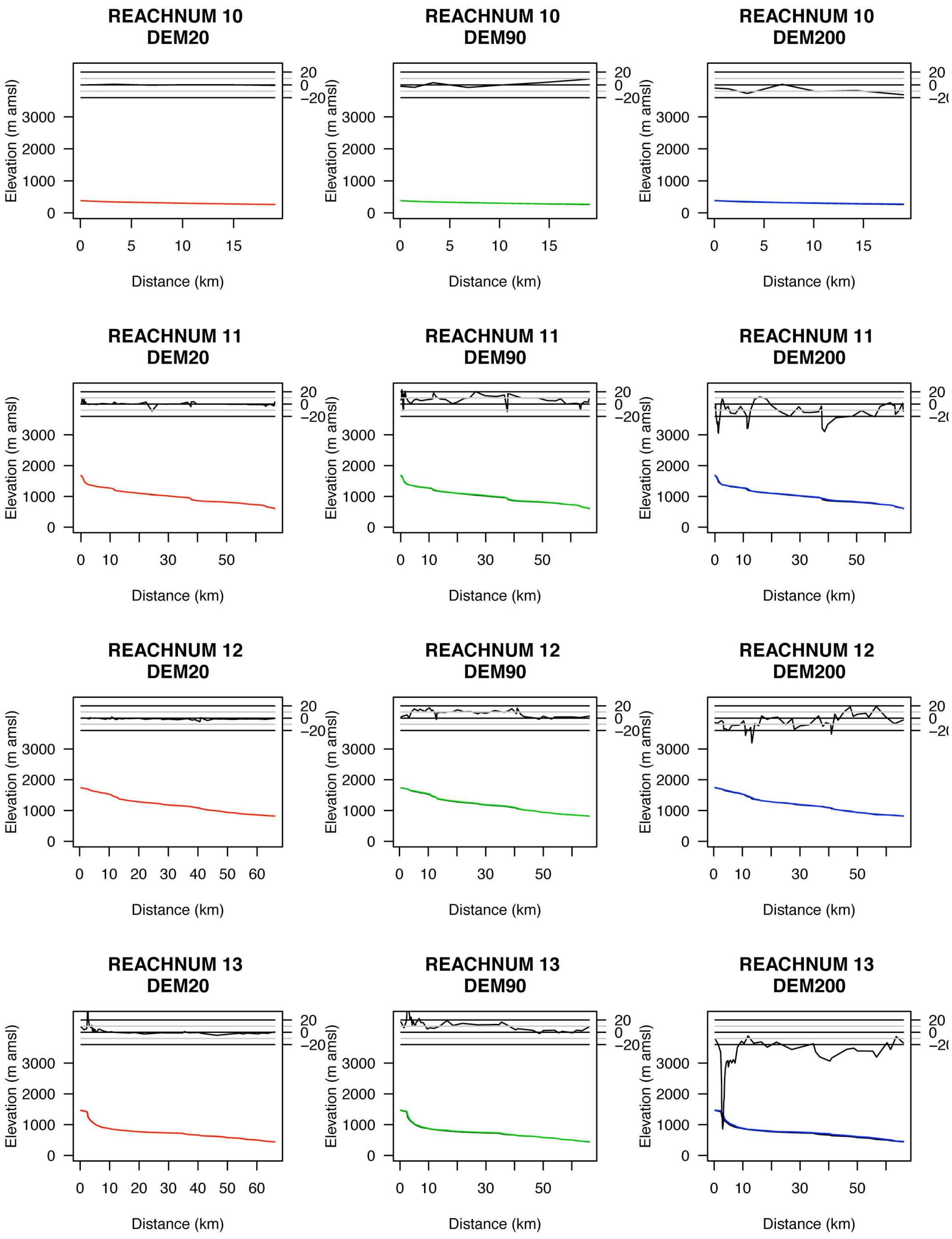
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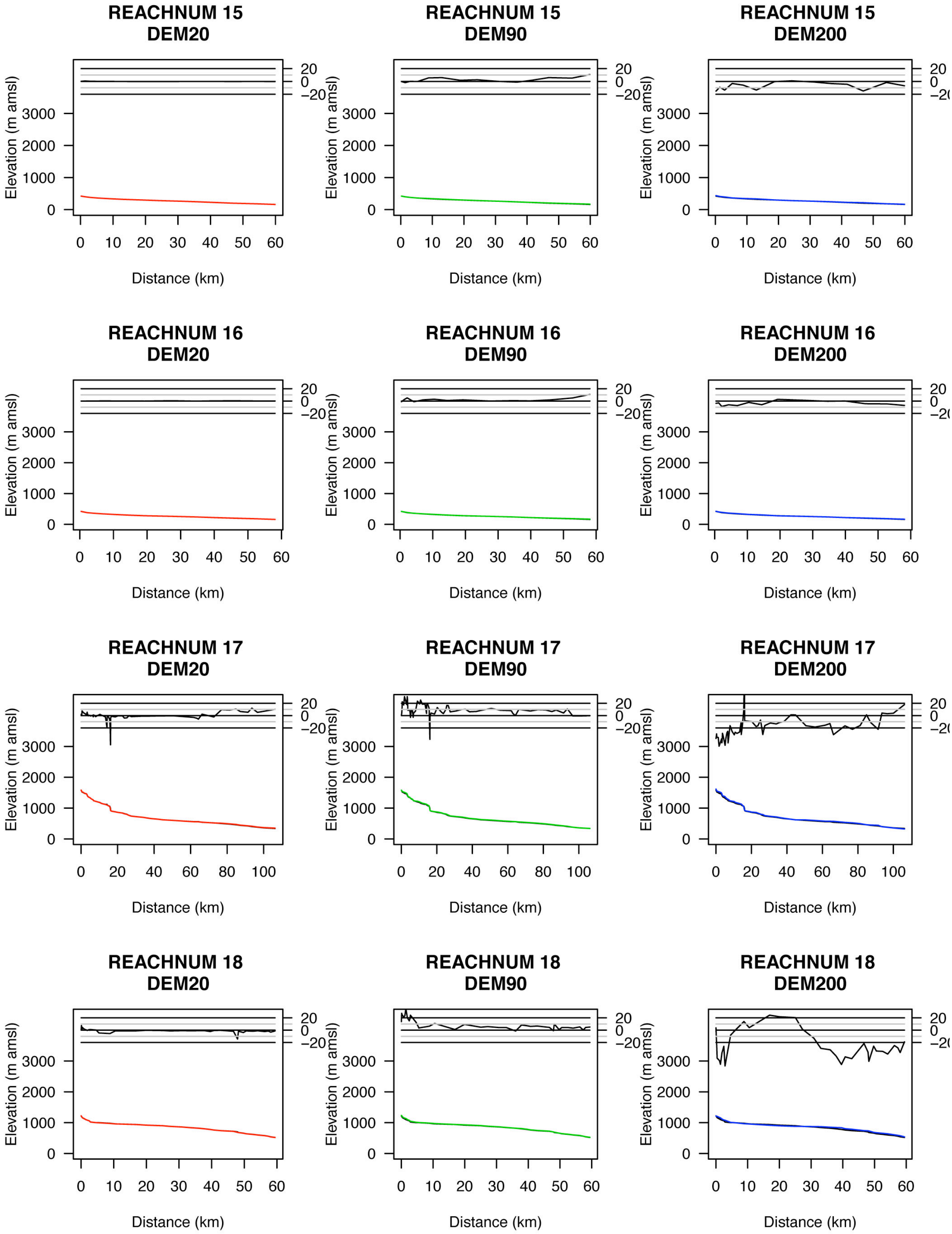

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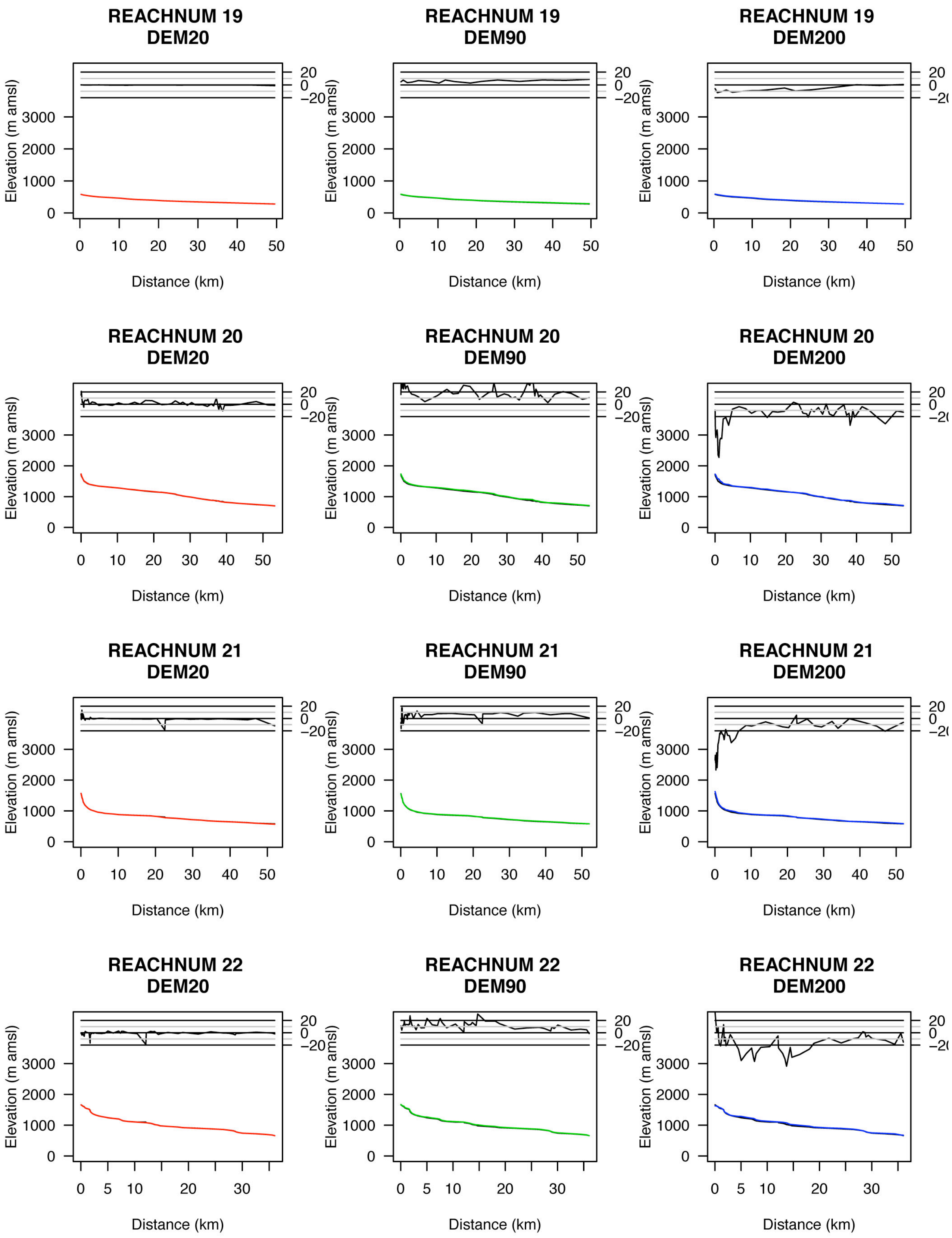
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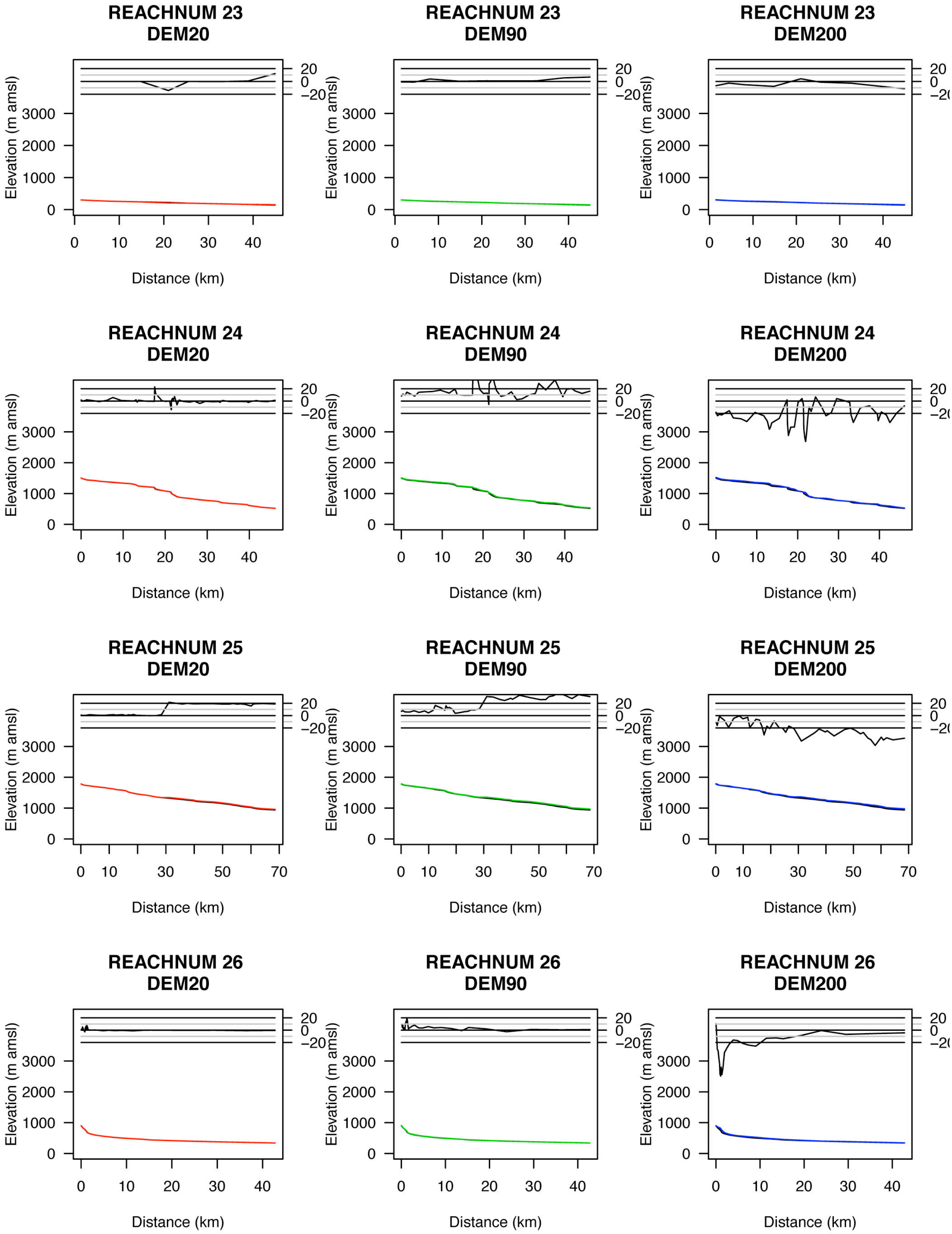
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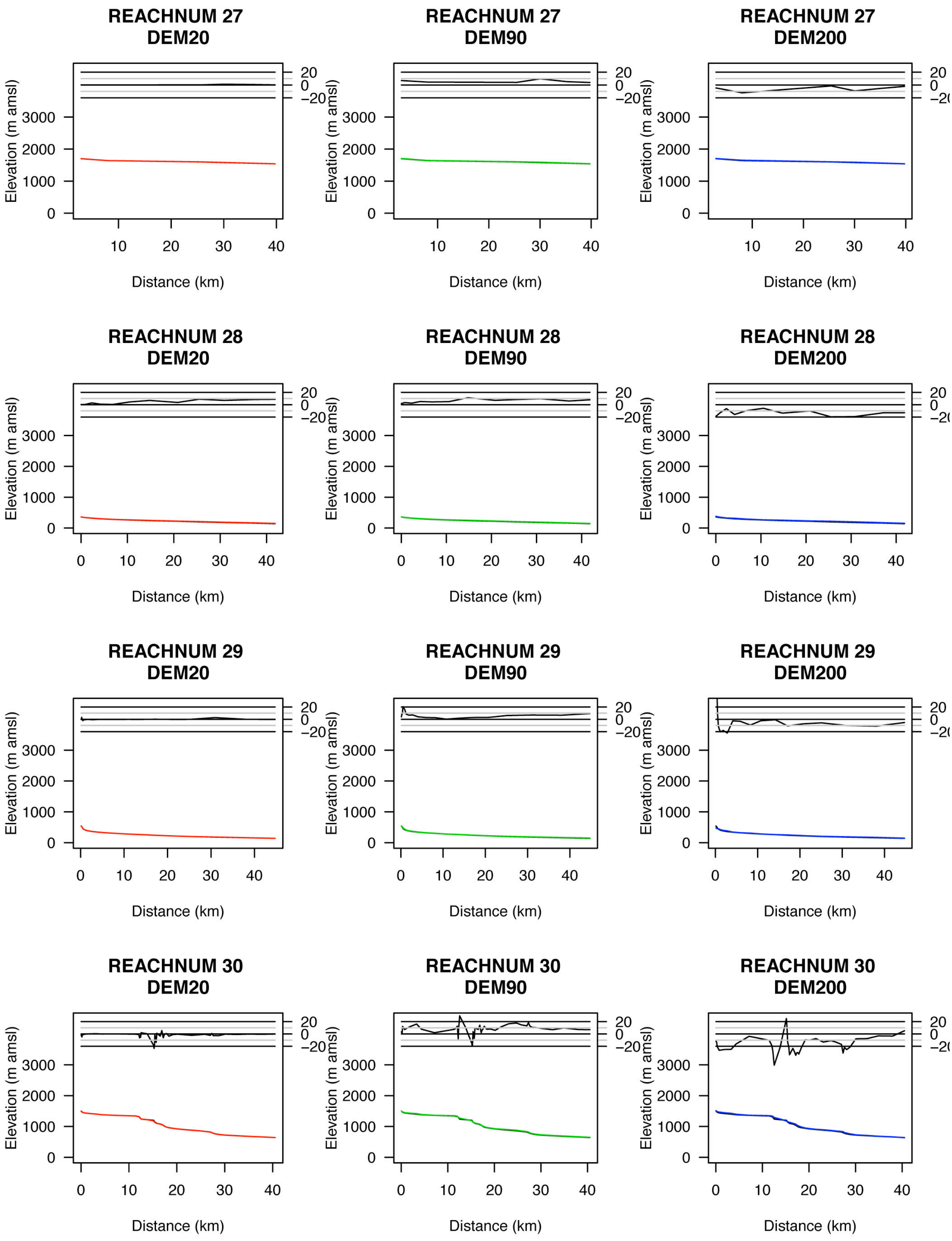
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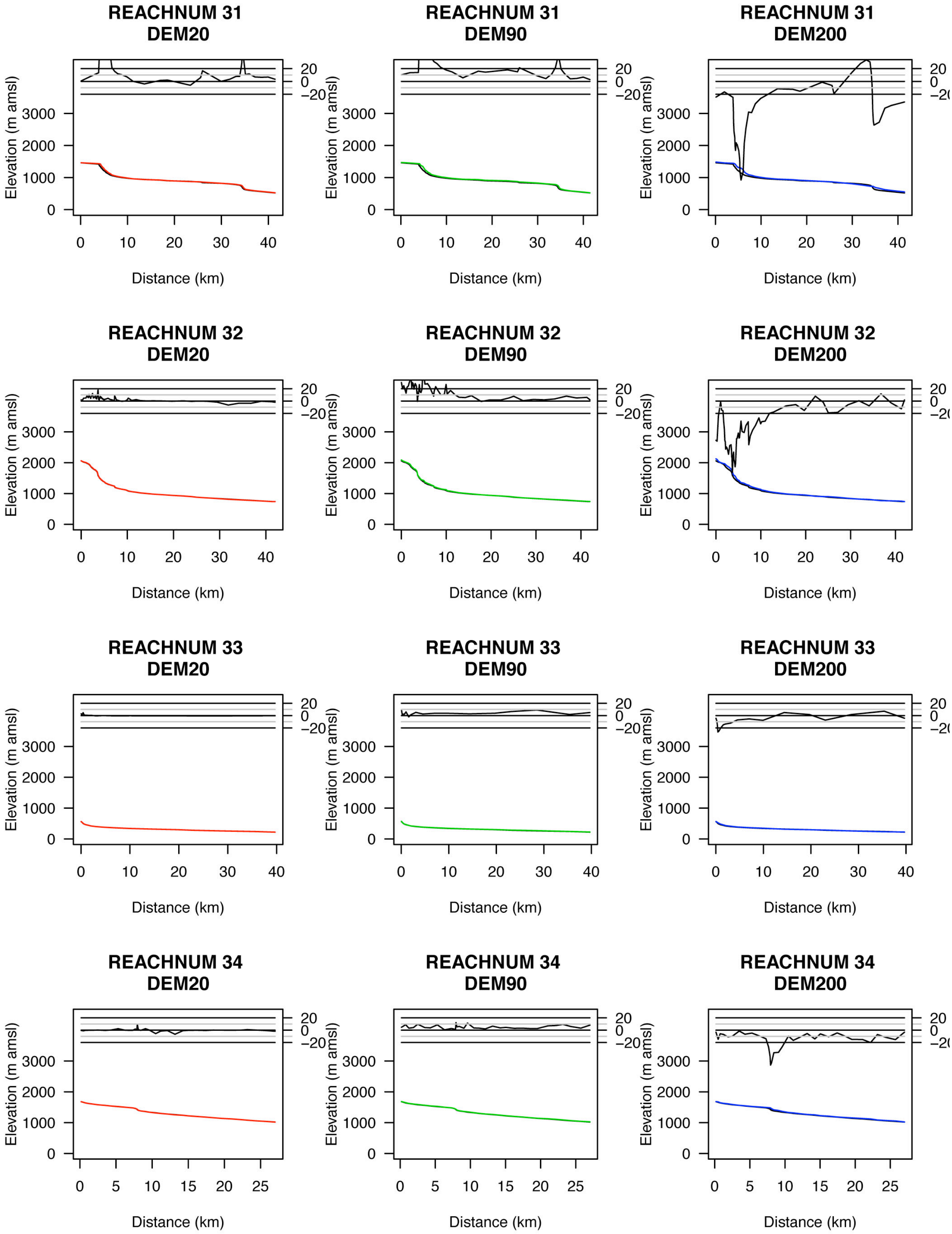
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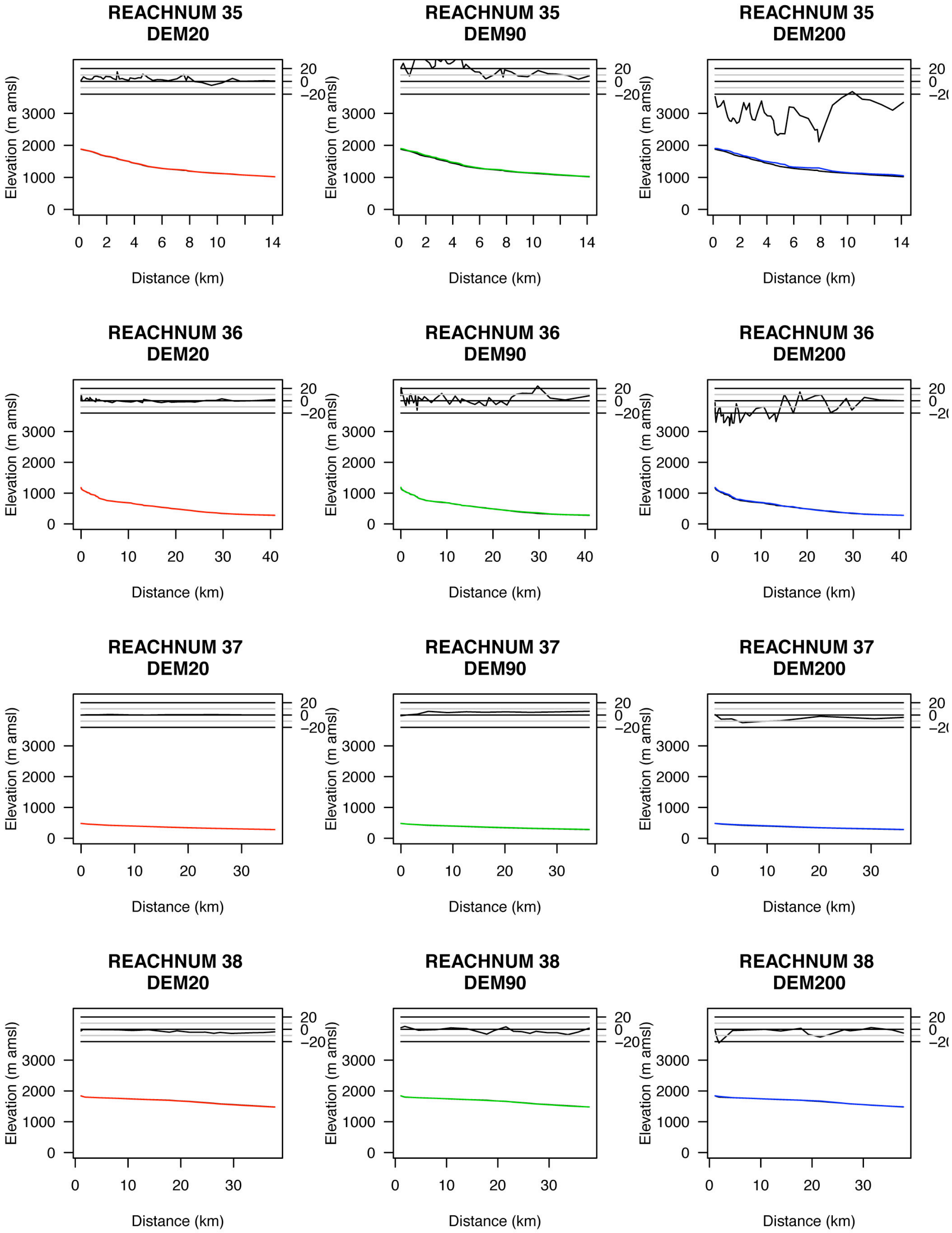
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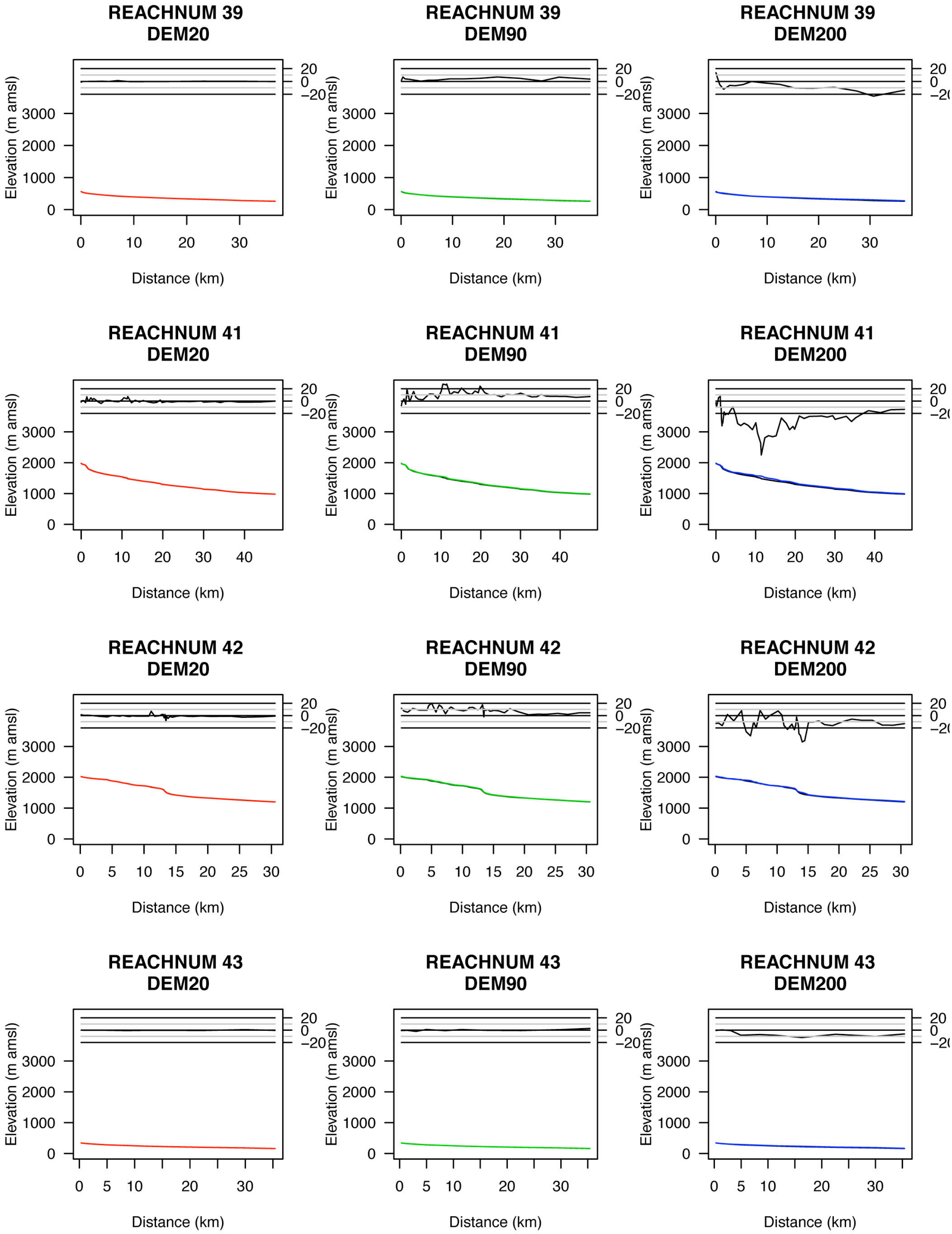

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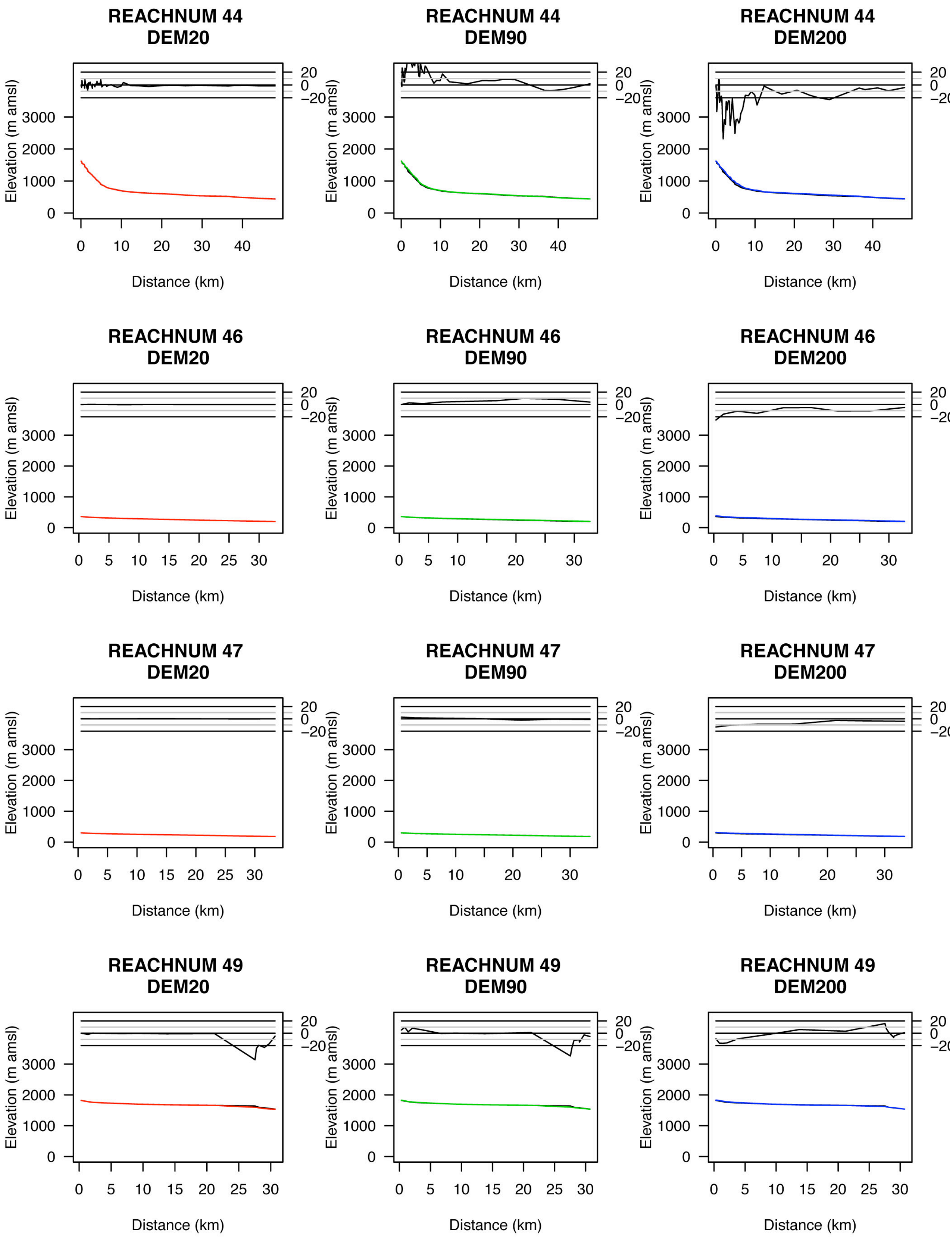
Distance (km)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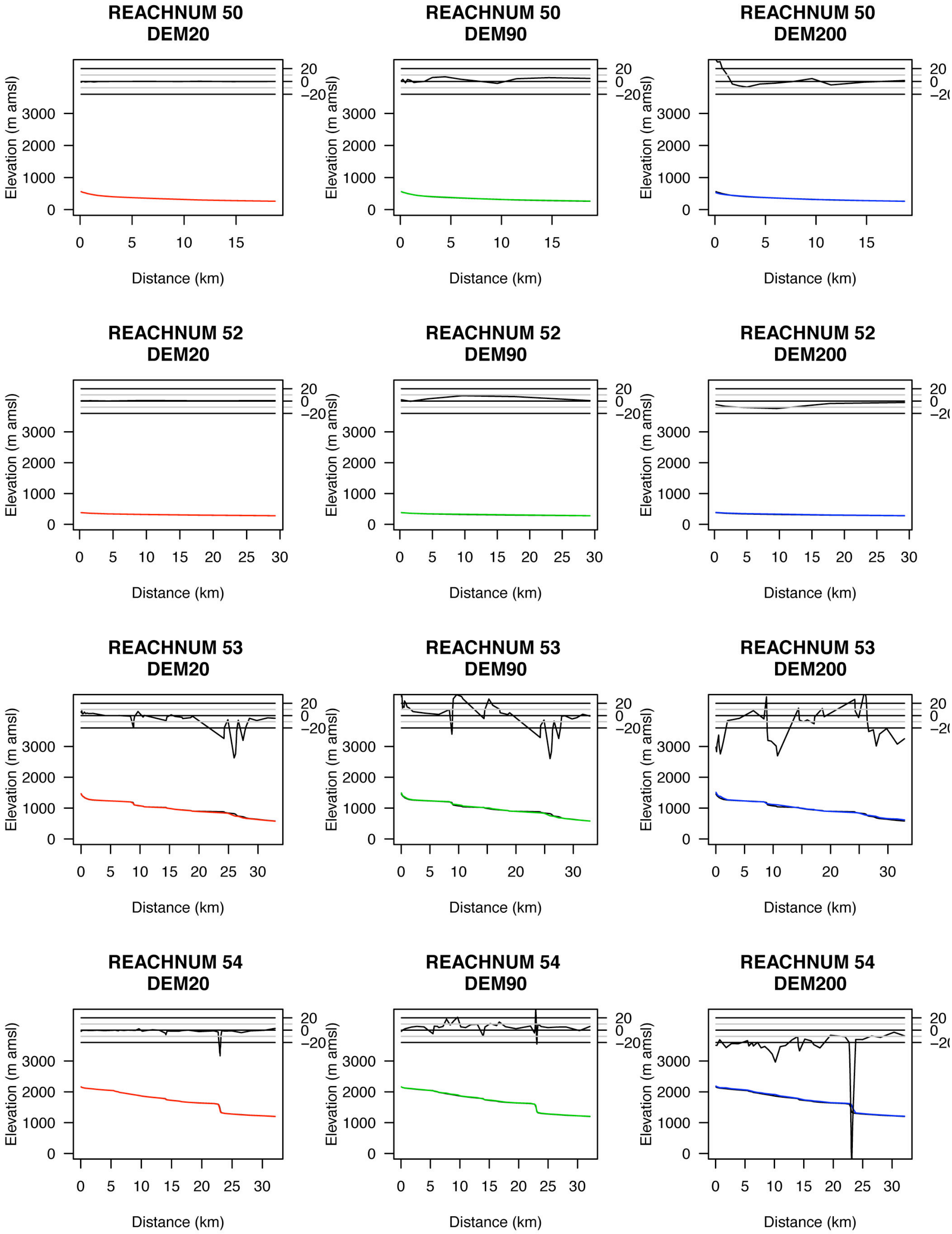
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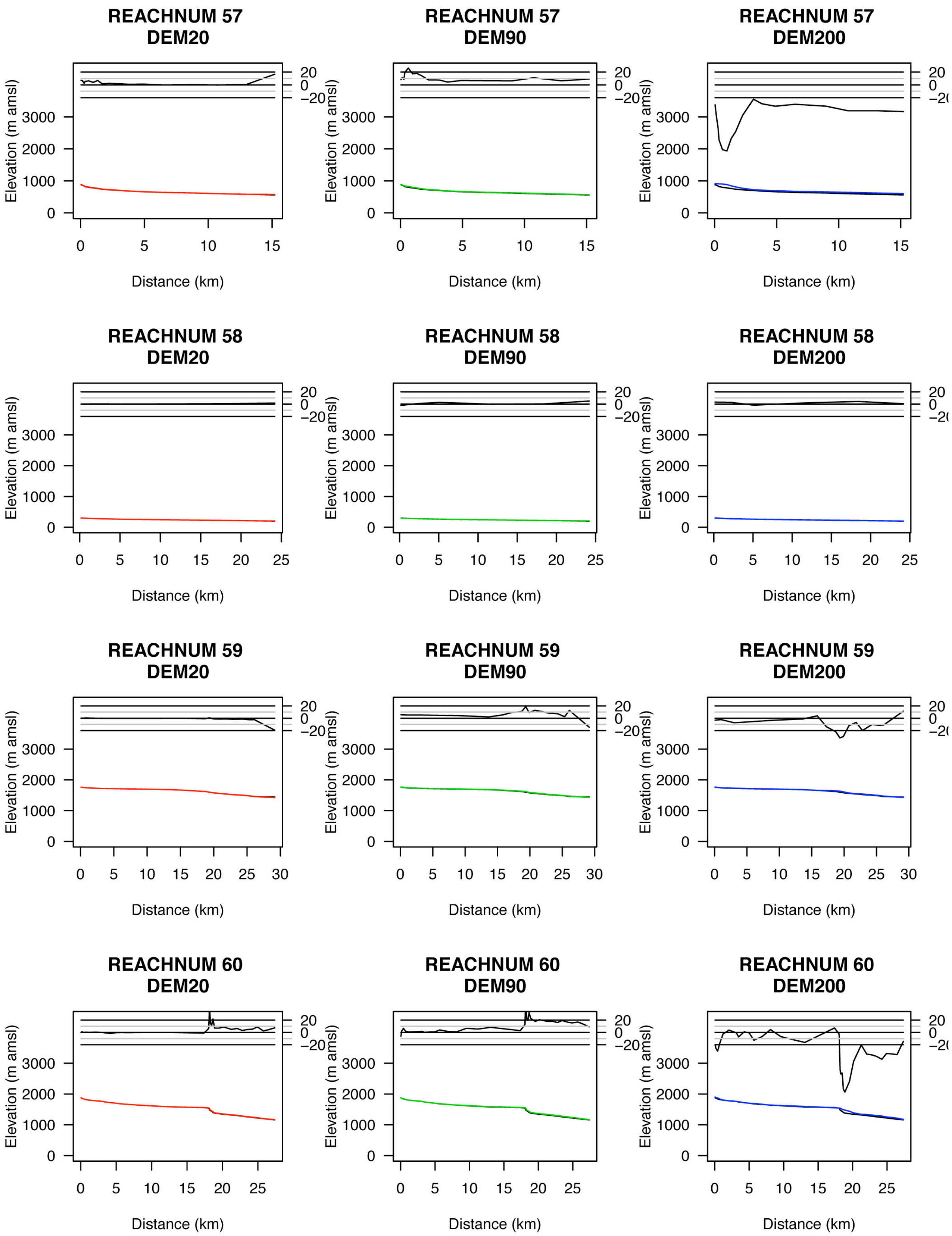
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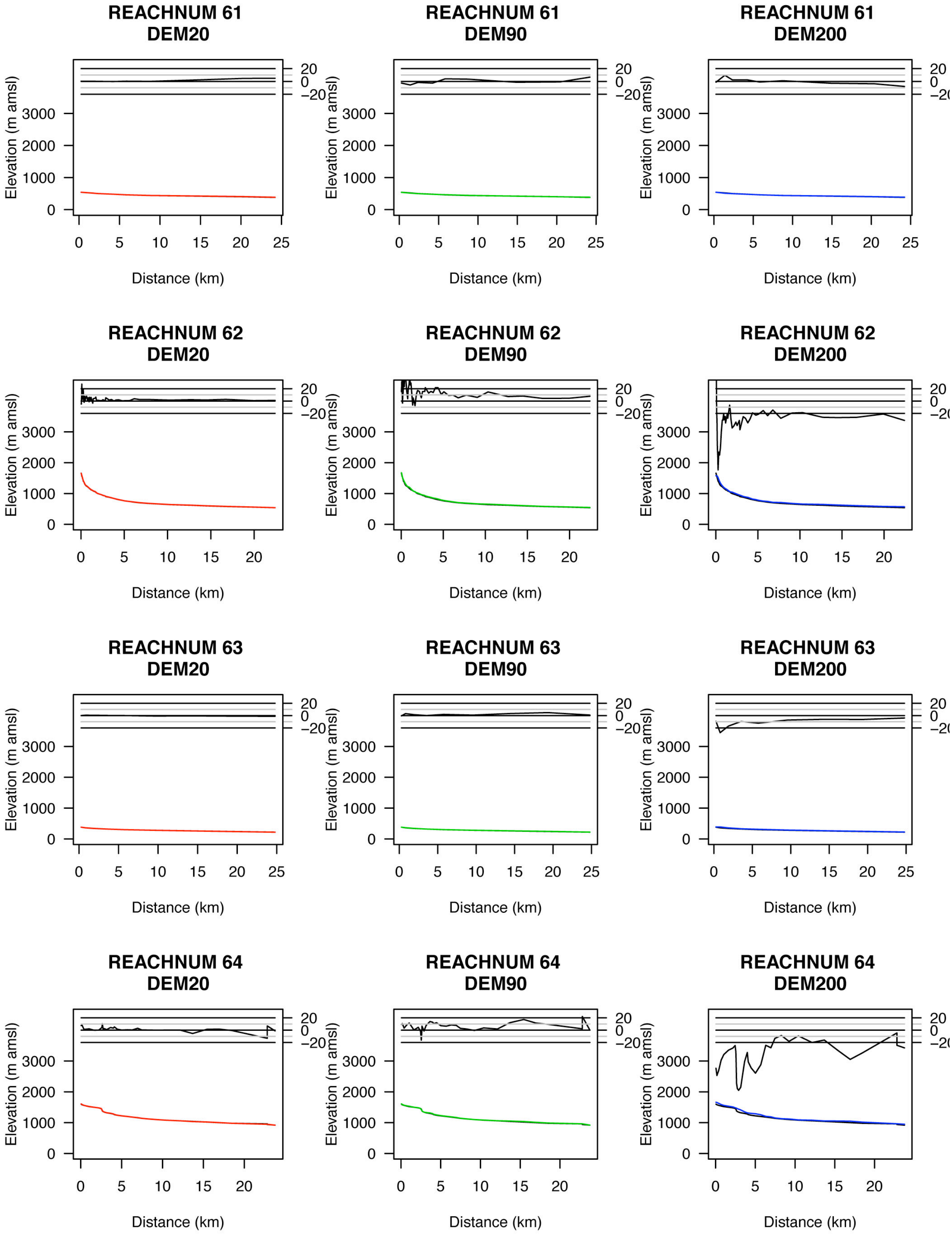
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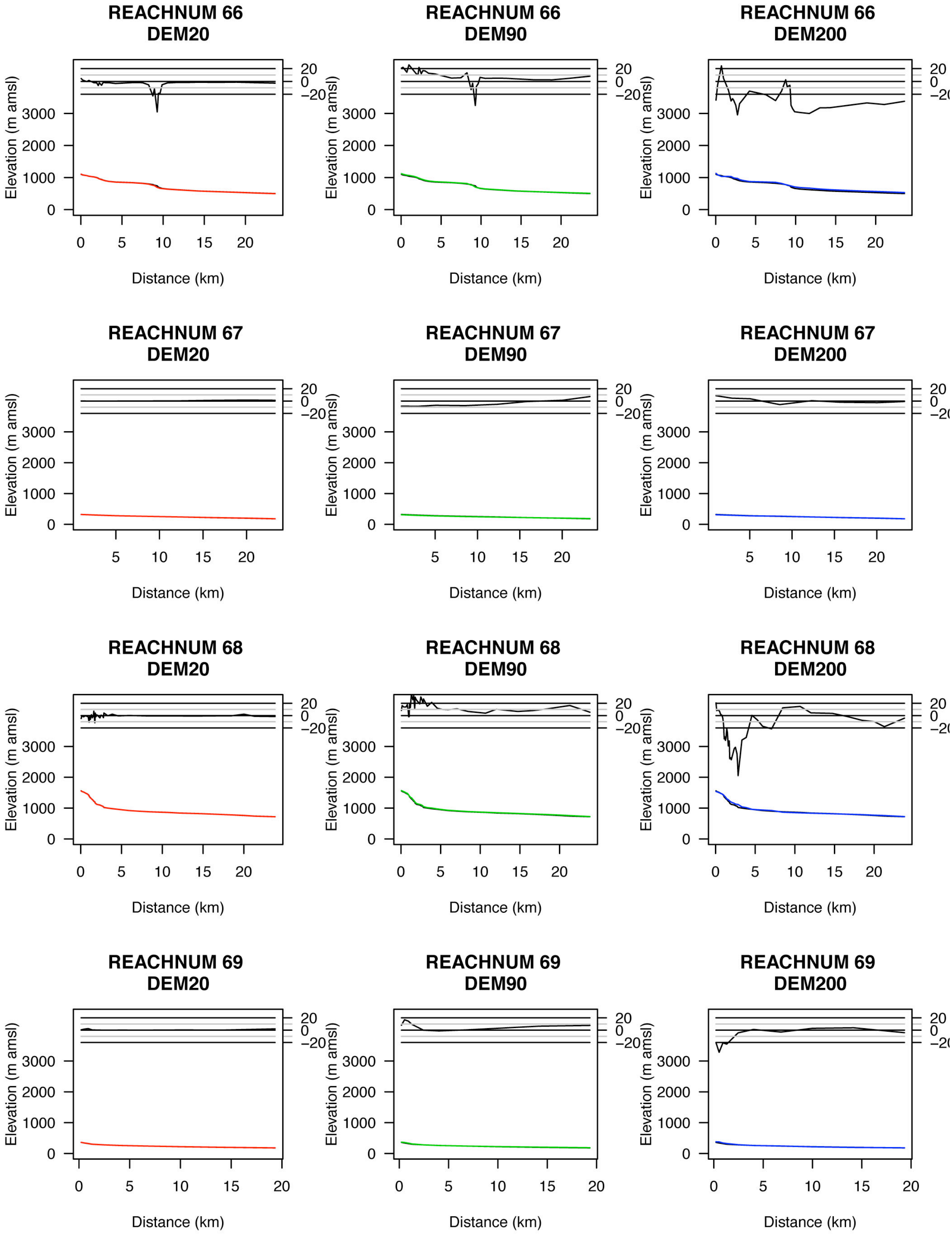
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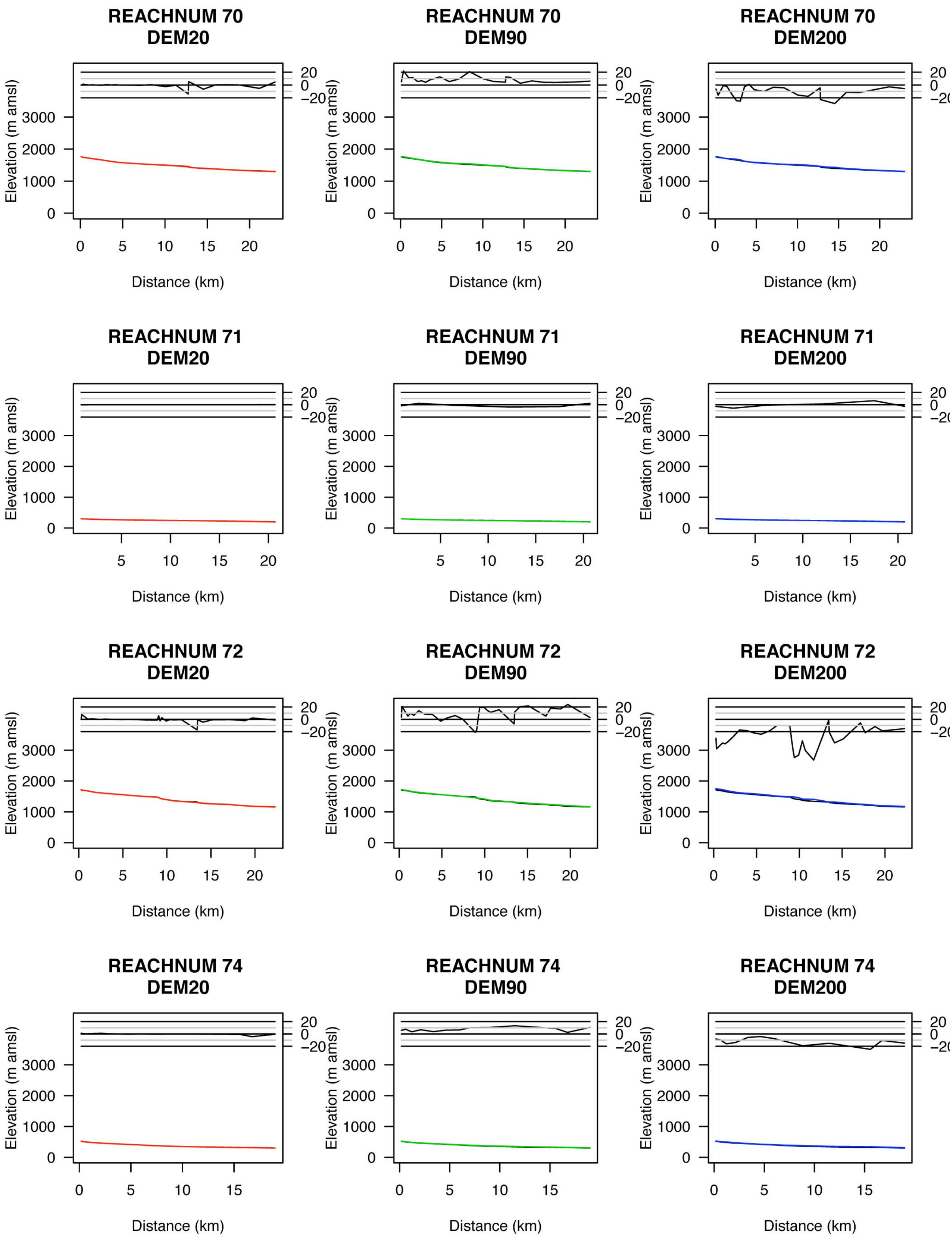
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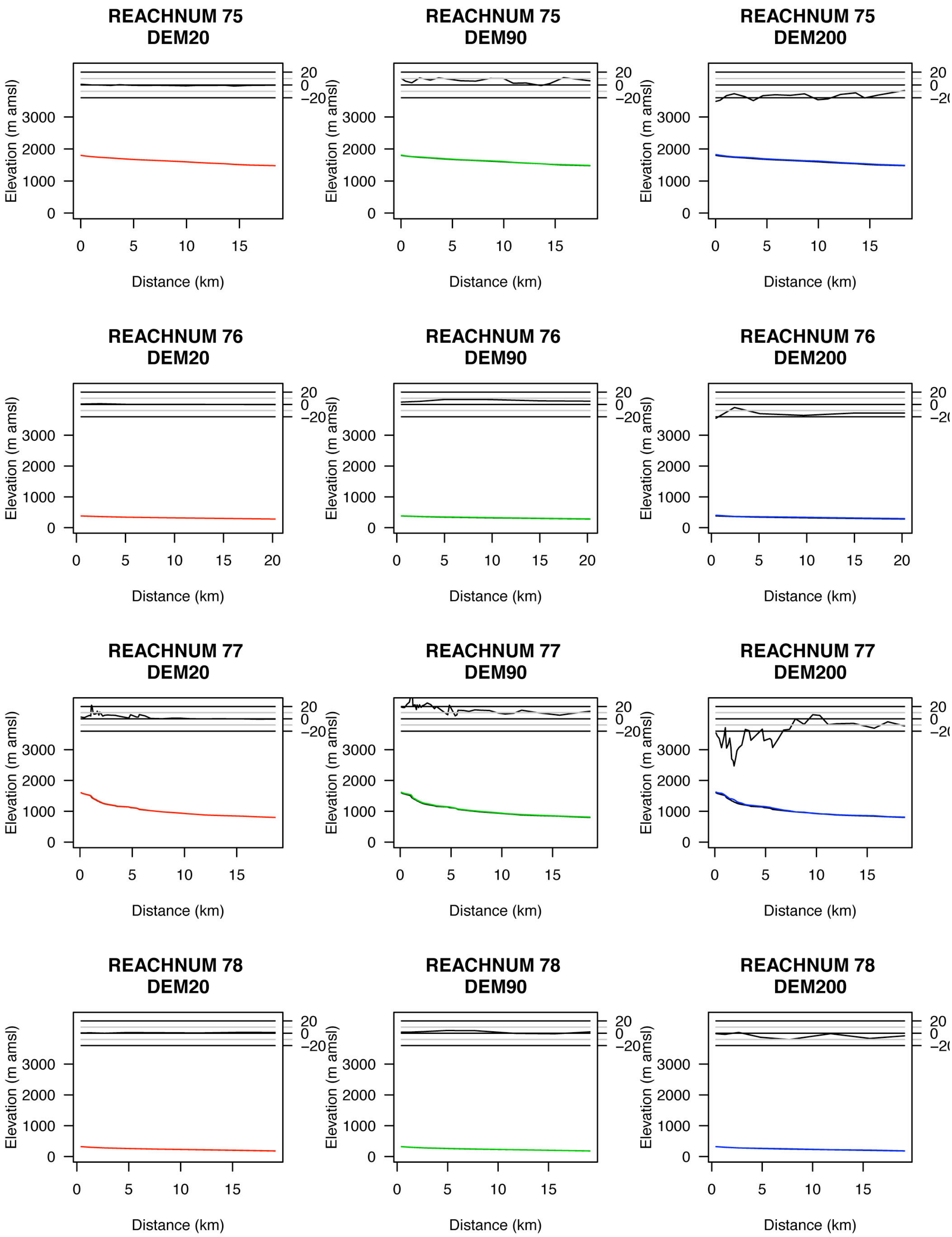
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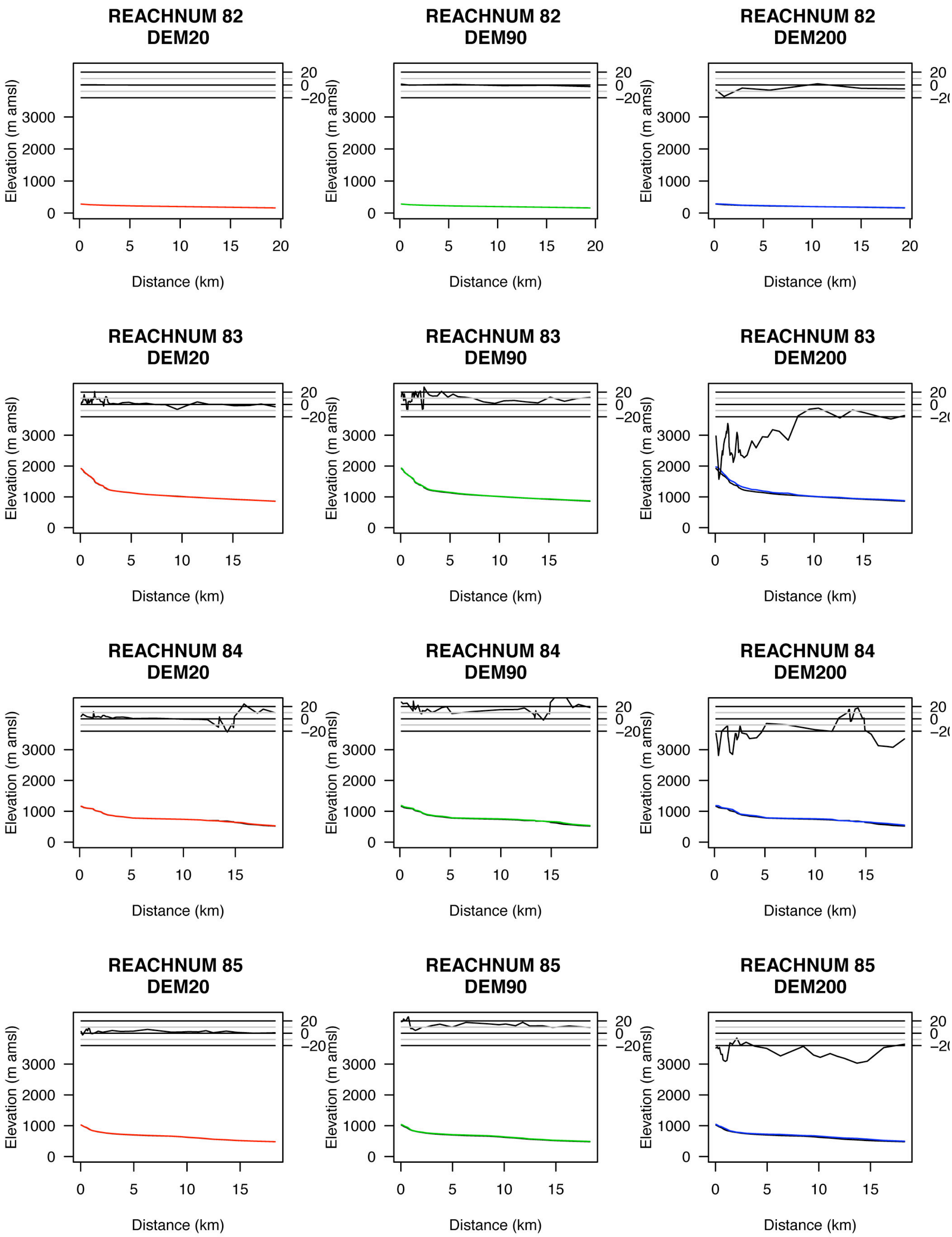
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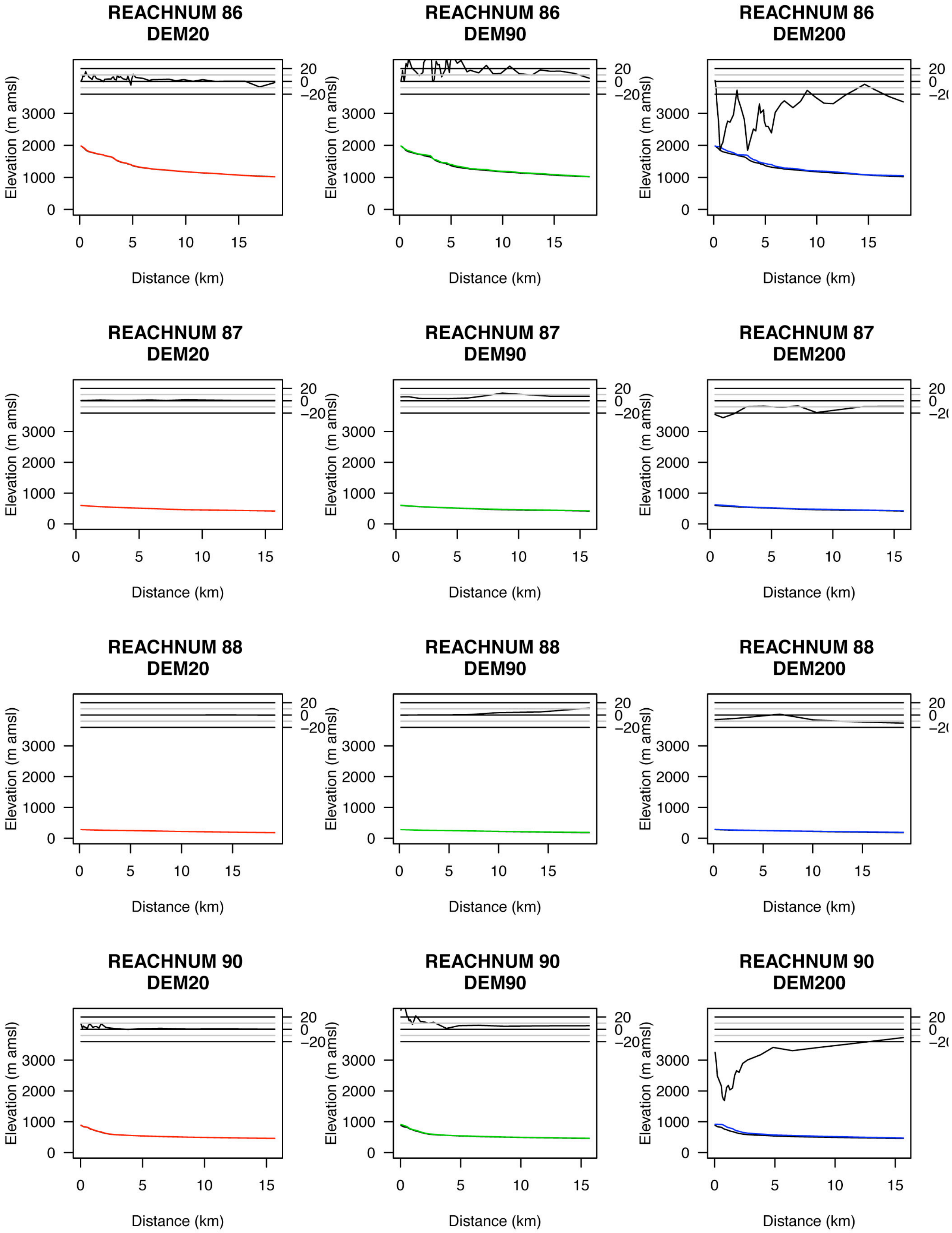
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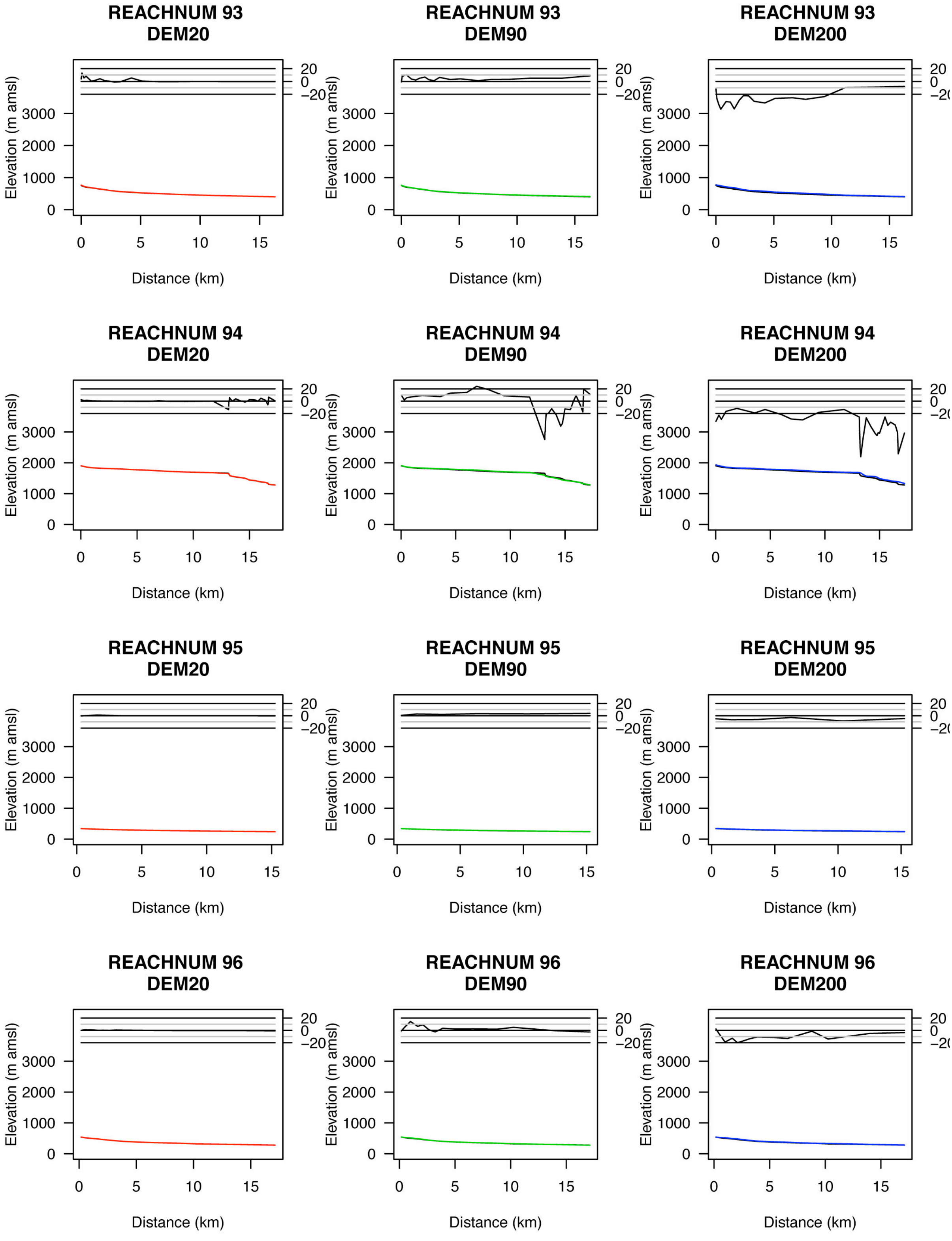
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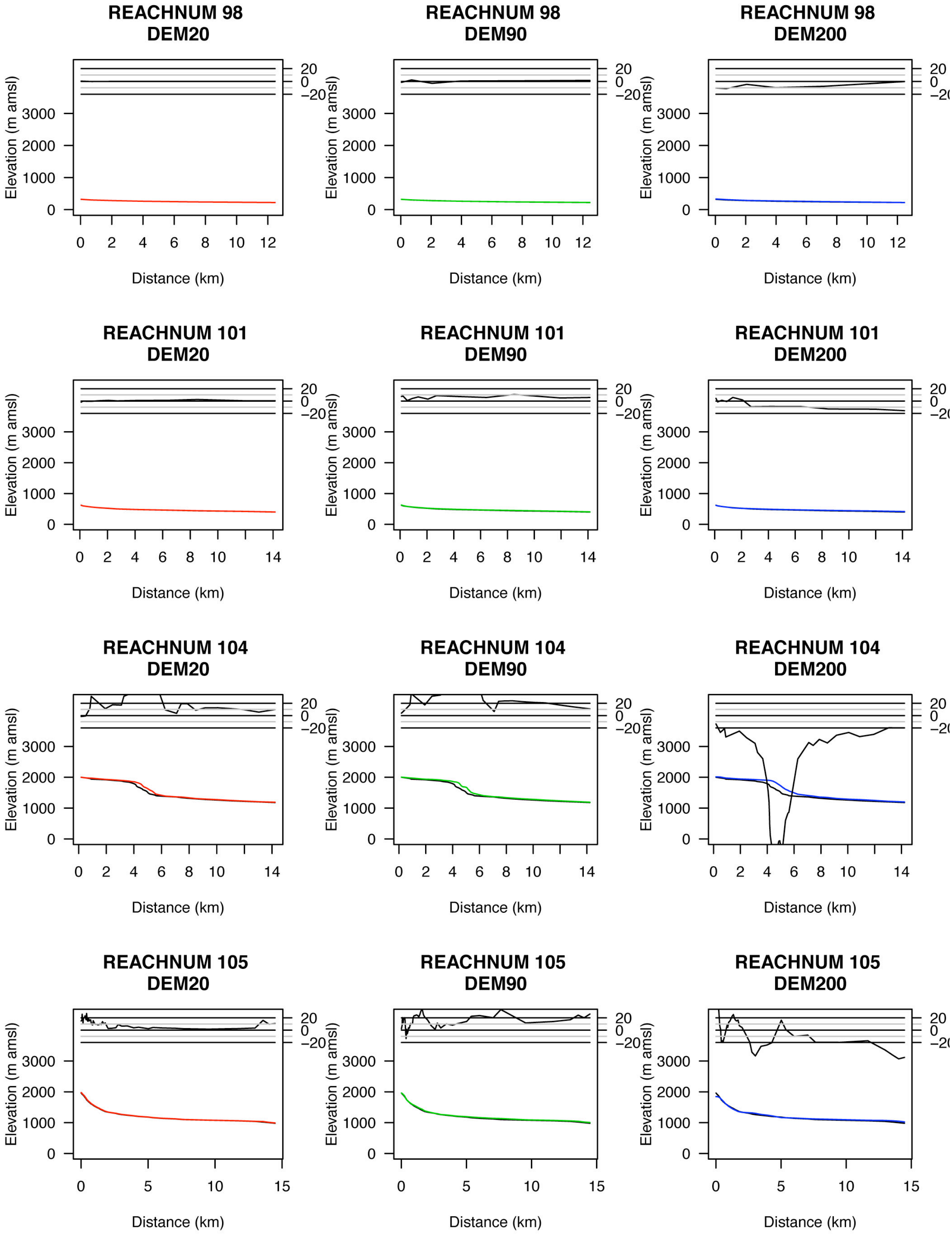
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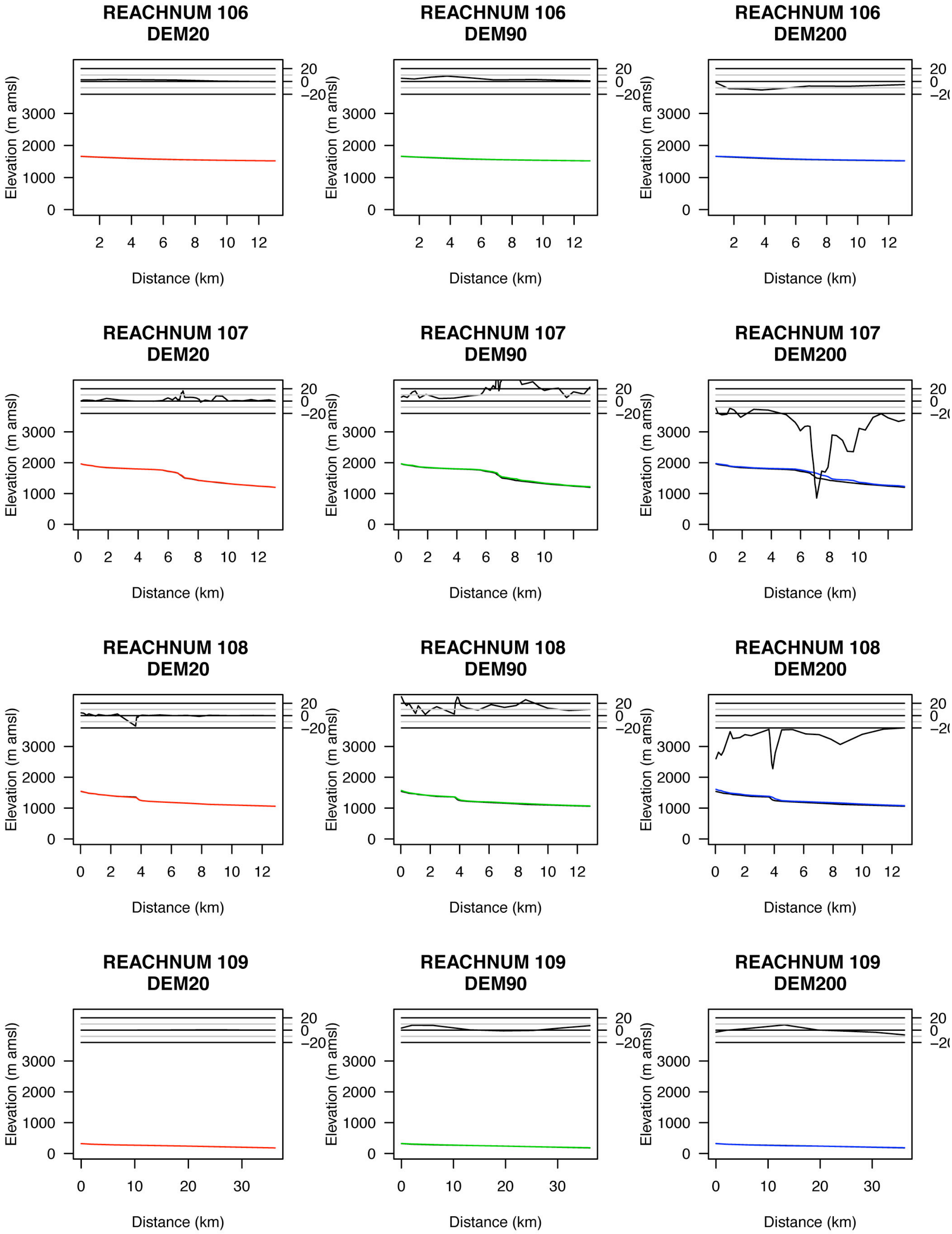
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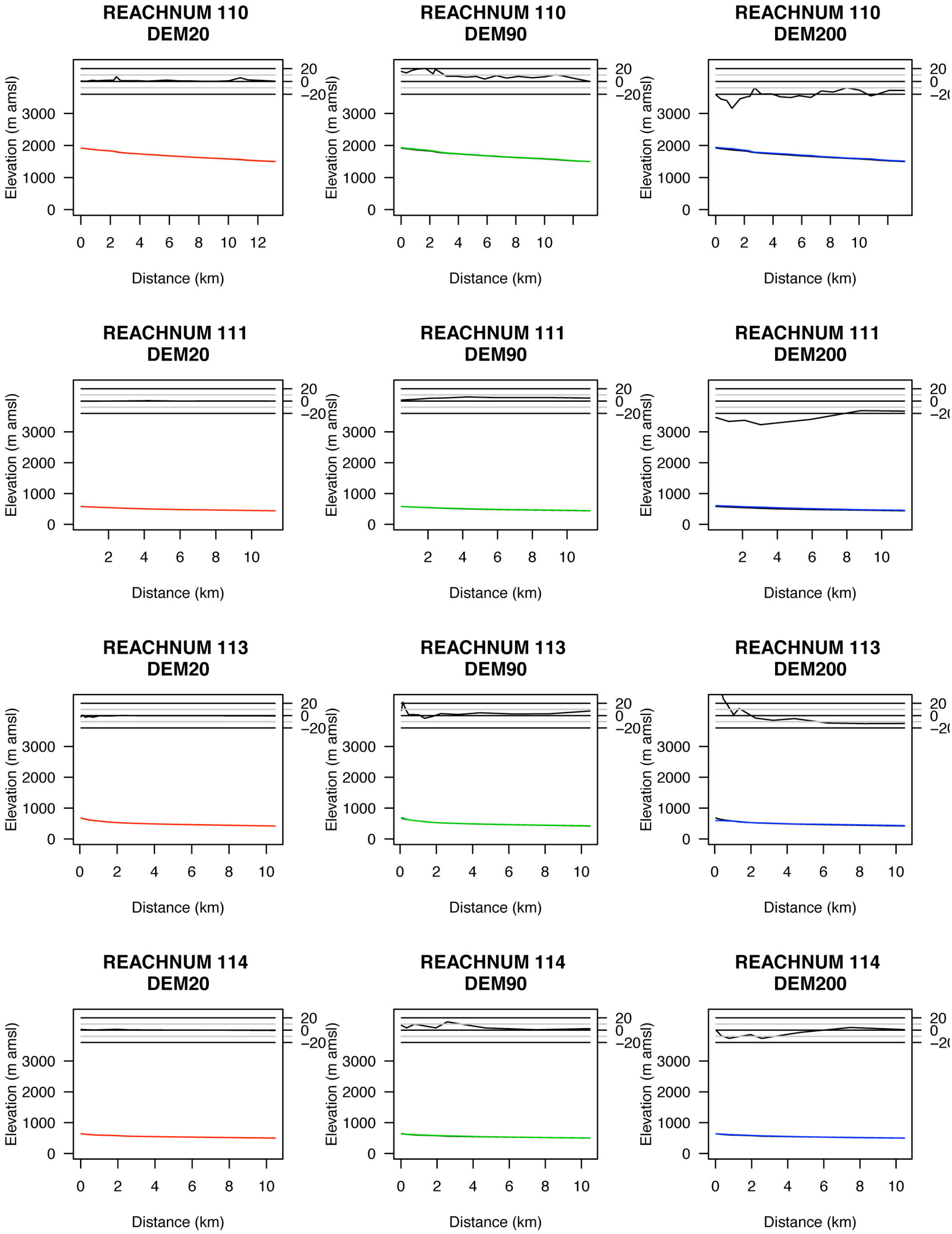
Distance (km)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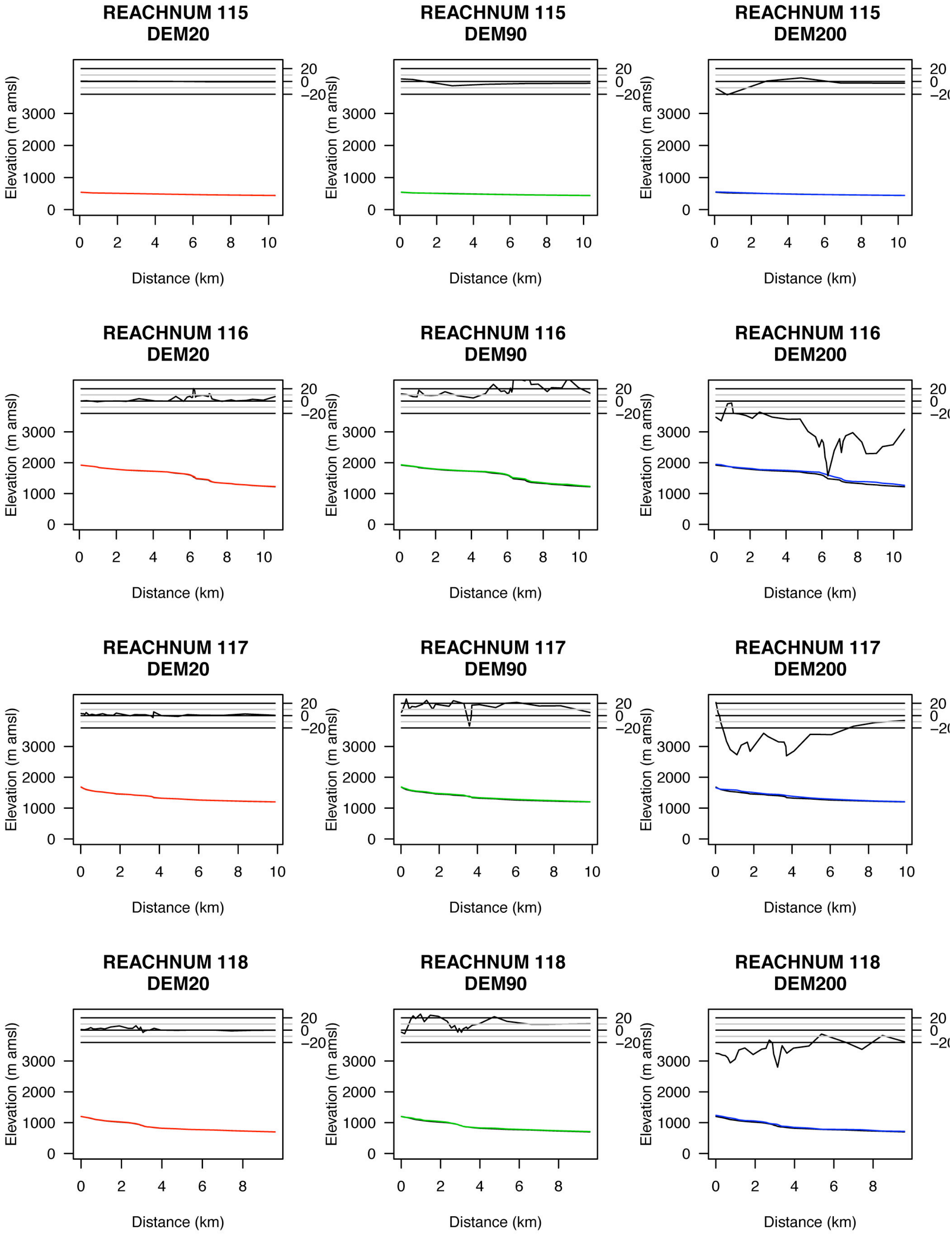
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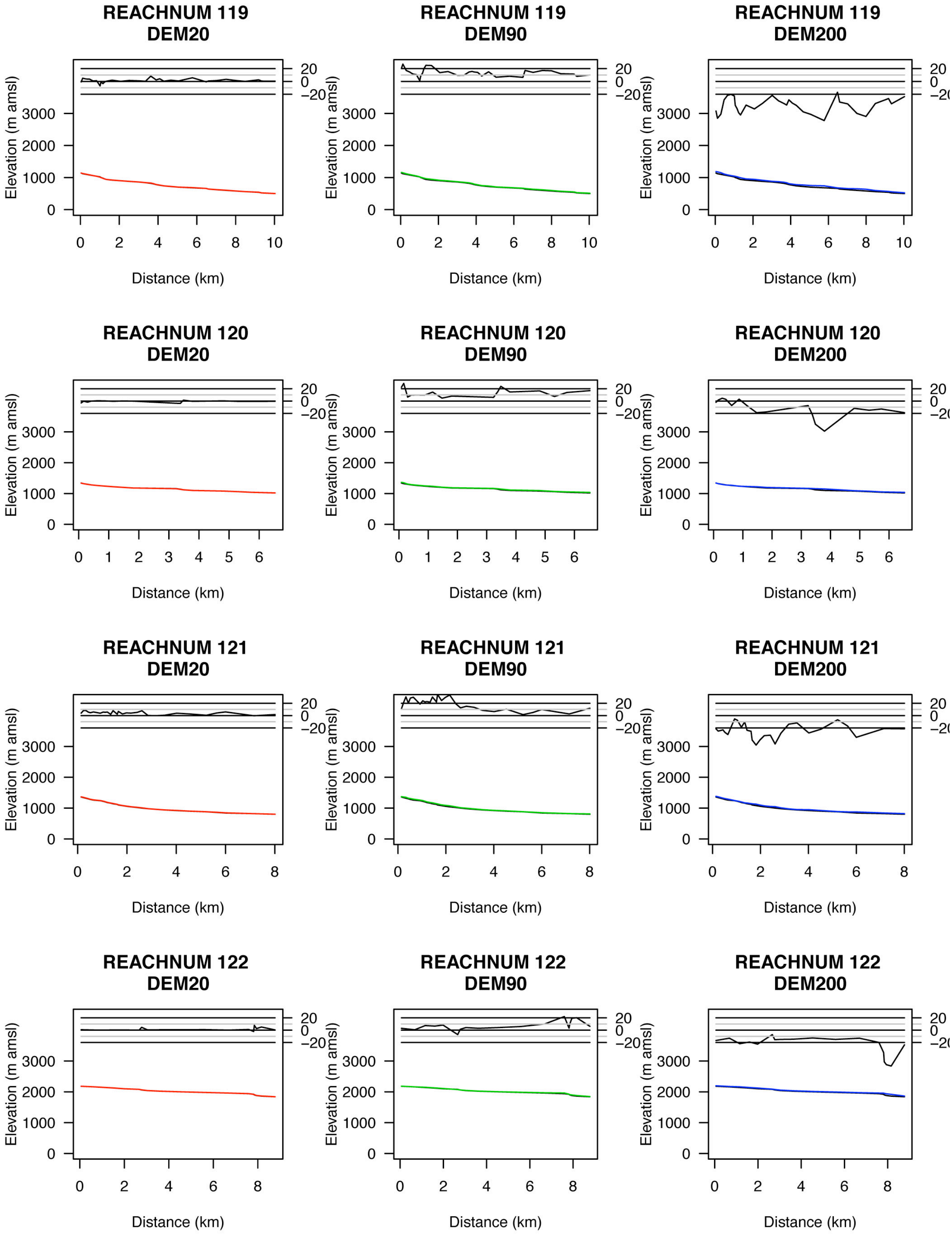
6
8
10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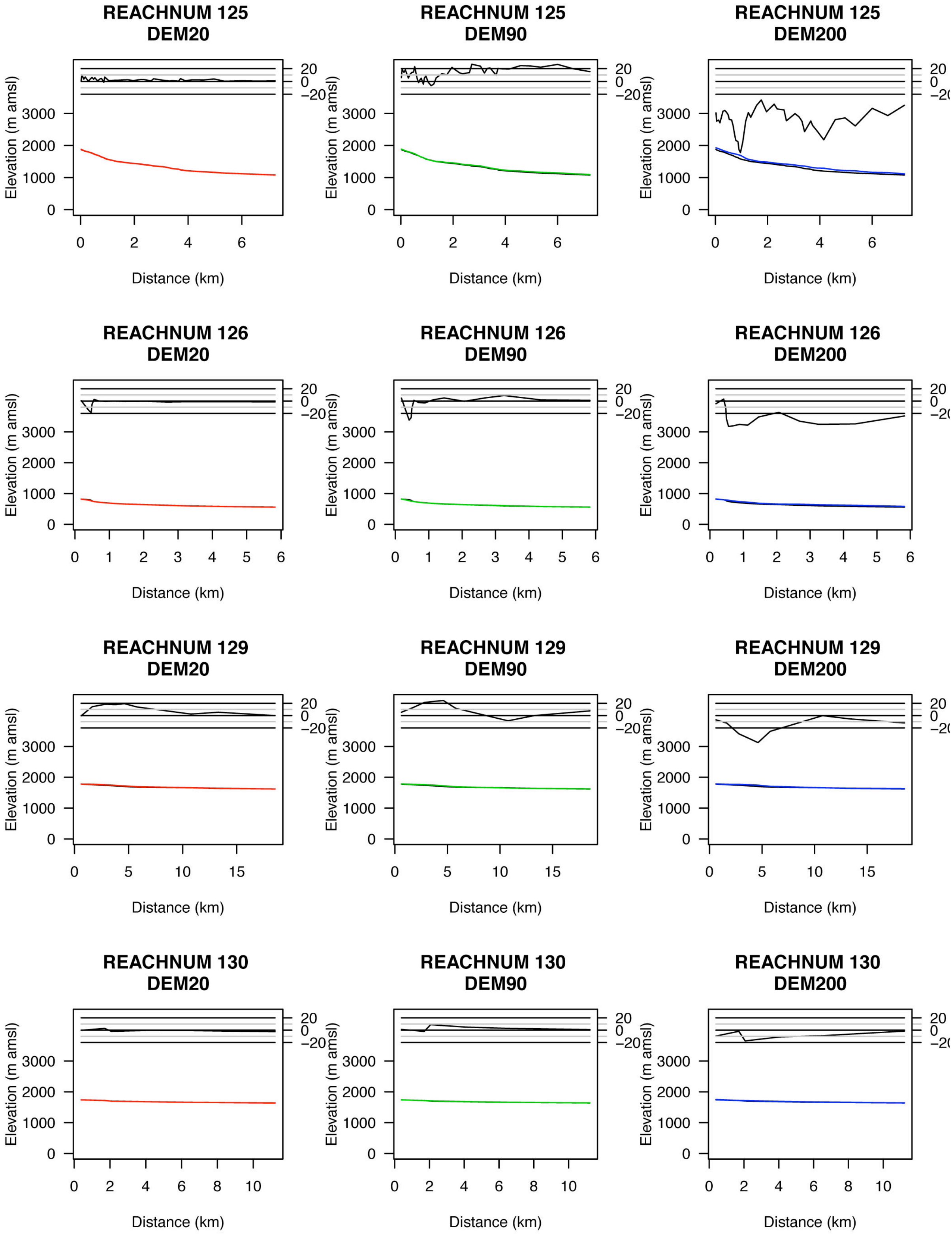
REACHNUM 119
DEM90
REACHNUM 119
DEM200
REACHNUM 120
DEM20
REACHNUM 120
DEM90
REACHNUM 120
DEM200
REACHNUM 121
DEM20
REACHNUM 121
DEM90
REACHNUM 121
DEM200
REACHNUM 122
DEM20
REACHNUM 122
DEM90
REACHNUM 122
DEM200
Elevation (m amsl)
Distance (km)
20
0
−20
0
1000
2000
3000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REACHNUM 125
DEM90
REACHNUM 125
DEM200
REACHNUM 126
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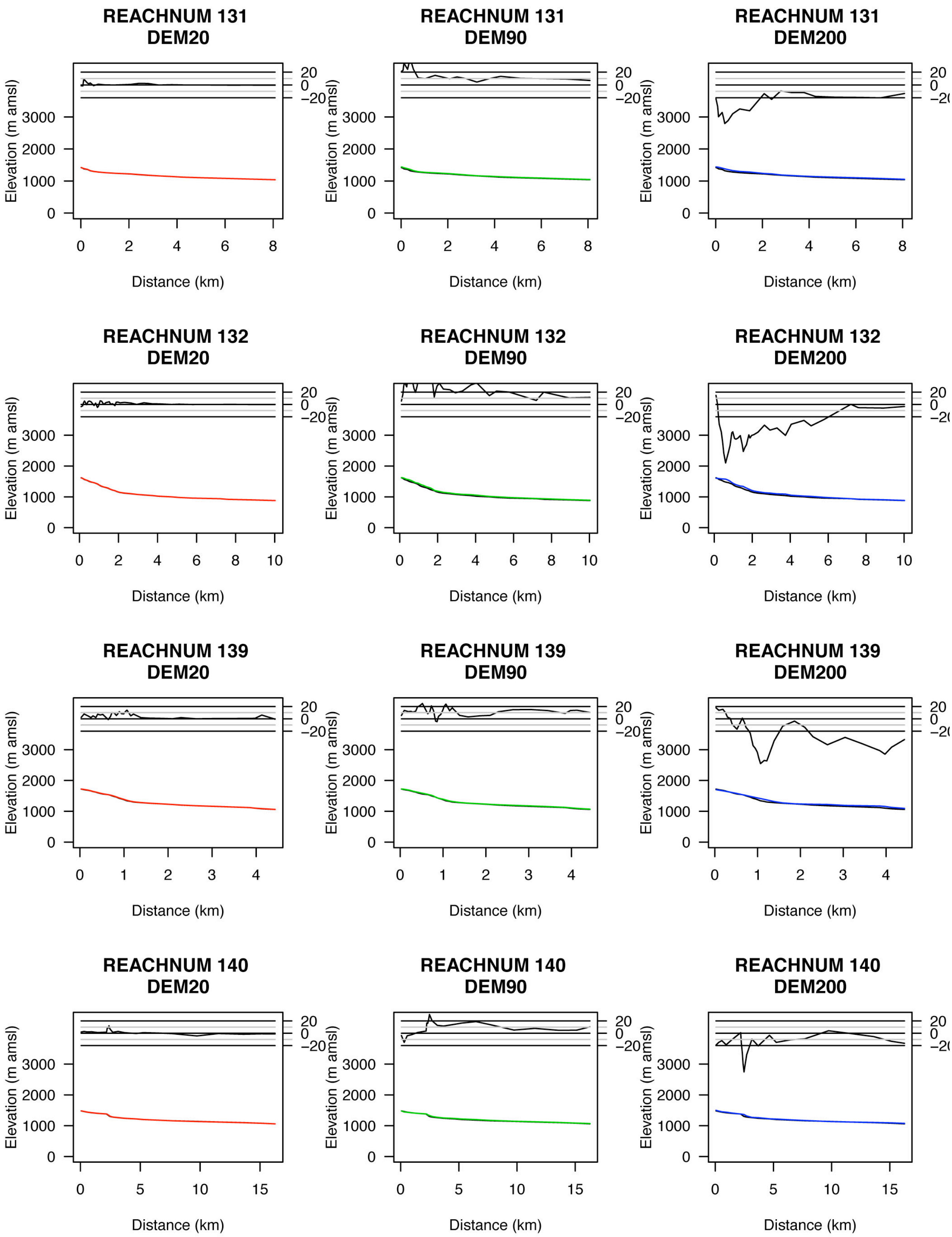
REACHNUM 126
DEM90
REACHNUM 126
DEM200
REACHNUM 129
DEM20
REACHNUM 129
DEM90
REACHNUM 129
DEM200
REACHNUM 130
DEM20
REACHNUM 130
DEM90
REACHNUM 130
DEM200
Elevation (m amsl)
Distance (km)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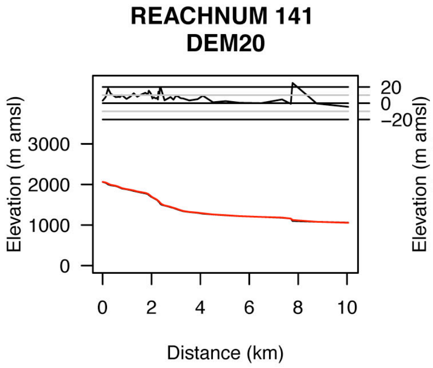
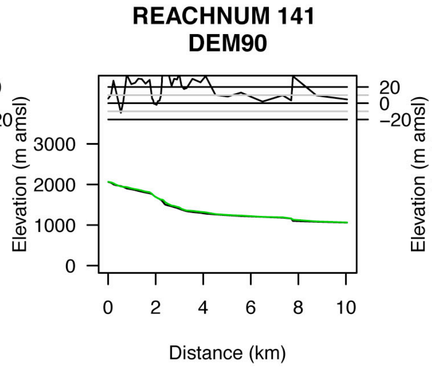
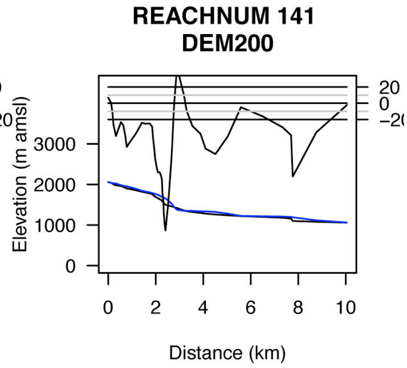
REACHNUM 131
DEM90
REACHNUM 131
DEM200
REACHNUM 132
DEM20
REACHNUM 132
DEM90
REACHNUM 132
DEM200
REACHNUM 139
DEM20
REACHNUM 139
DEM90
REACHNUM 139
DEM200
REACHNUM 140
DEM20
REACHNUM 140
DEM90
REACHNUM 140
DEM200
Elevation (m amsl)
Distance (km)
20
0
−20
0
1000
2000
3000


REACHNUM 141
DEM20
Elevation (m amsl)
Distance (km)


REACHNUM 141
DEM90
Elevation (m amsl)
Distance (km)


REACHNUM 141
DEM200
Elevation (m amsl)
Distance (km)

APPENDIX C

Absolute mean difference in elevation between contour and DEM20, DEM90 and DEM200 profiles

REACHNUM	Abs Mean Diff20	Abs Mean Diff90	Abs Mean Diff200
1	3.382	3.333	14.706
2	2.892	11.361	29.457
4	1.276	0.163	0.125
5	6.602	16.814	25.294
6	7.505	1.227	9.721
7	0.476	5.708	10.109
8	1.400	5.041	14.821
9	5.427	13.705	56.270
10	0.029	0.824	8.308
11	0.687	7.623	16.130
12	1.064	7.702	7.446
13	8.368	21.689	51.932
15	0.005	2.603	6.534
16	0.142	2.244	3.541
17	2.487	6.863	15.260
18	1.070	10.075	24.566
19	0.294	5.820	6.789
20	1.840	21.721	21.947
21	0.612	3.338	34.609
22	1.800	12.283	14.896
23	0.220	1.904	4.512
24	0.752	17.654	23.765
25	9.244	18.510	22.247
26	0.906	5.582	28.842
27	0.475	5.737	5.810
28	4.408	6.051	13.263
29	0.062	7.701	1.857
30	2.777	7.706	17.662
31	28.641	38.863	52.773
32	3.940	16.550	49.679
33	0.549	3.808	8.707
34	0.059	5.150	15.951
35	4.128	23.395	51.600
36	0.346	3.372	15.891
37	0.373	3.709	6.026
38	3.549	1.681	4.351
39	0.016	3.593	6.529
41	0.309	10.019	29.957
42	0.924	9.148	12.601
43	0.196	0.117	5.899
44	0.289	23.998	31.914
46	0.198	4.505	11.502
47	0.085	0.291	7.287
49	10.747	5.134	3.276
50	0.289	2.078	6.897
52	0.532	3.608	7.182
53	8.953	0.859	19.198

54	7.961	5.093	55.270
57	3.765	11.129	53.814
58	0.516	1.086	1.852
59	1.836	6.900	10.003
60	6.408	13.056	29.449
61	1.475	0.007	0.106
62	3.668	16.773	34.992
63	0.175	1.827	10.995
64	1.837	5.672	44.058
66	6.458	6.140	26.374
67	0.569	3.599	0.807
68	1.367	16.272	25.002
69	0.820	6.527	10.274
70	0.650	8.510	11.321
71	0.057	0.821	0.700
72	0.641	8.178	29.447
74	0.501	7.087	12.281
75	0.477	6.830	17.745
76	0.296	5.971	14.695
77	5.229	19.569	29.696
78	0.865	2.008	3.890
82	0.058	0.312	6.925
83	4.817	10.893	60.301
84	1.030	15.993	17.933
85	2.589	14.362	29.940
86	4.215	18.811	53.837
87	0.758	6.244	14.676
88	0.022	3.380	7.263
90	3.668	15.509	66.554
93	2.195	4.666	25.840
94	0.277	8.117	40.338
95	0.106	2.714	5.536
96	0.186	3.229	10.307
98	0.142	0.181	7.267
101	0.416	6.136	4.812
104	60.024	73.690	113.498
105	11.487	14.129	2.632
106	2.010	4.532	8.667
107	3.465	23.255	57.168
108	0.310	16.221	43.011
109	0.218	3.600	0.585
110	1.615	10.166	21.134
111	0.048	4.583	28.239
113	0.758	4.370	14.523
114	0.533	5.651	5.136
115	0.013	1.754	5.120
116	4.128	19.575	55.825
117	1.556	14.085	30.324
118	1.580	9.742	32.793
119	1.355	13.698	37.413
120	0.745	13.418	12.702
121	4.149	18.669	24.110
122	1.371	7.113	24.004
125	2.690	12.895	61.566

126	3.175	3.216	26.817
129	10.166	10.905	19.174
130	0.457	2.842	8.371
131	0.943	16.661	29.859
132	1.376	30.404	43.056
139	4.745	11.747	25.971
140	2.097	9.375	16.673
141	8.375	20.533	46.256

APPENDIX D

Results of the Mann-Whitney-Wilcoxon test comparing 1:50 000 contour heights with DEM20, DEM90 and DEM200 -derived elevations for 109 river profiles in the X catchment
(n = sample size)

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
1	105	3849	0.000655	2192	0.0592790	1392	8.85E-06
2	105	1002	1.27E-08	522	5.02E-13	640	7.51E-12
4	16	129	0.0005798	62	0.7819519	68	1
5	49	234	9.11E-05	88	6.15E-09	64	5.62E-10
6	57	1607	5.75E-10	478	0.0056934	132	3.51E-08
7	19	147	0.0360679	3	1.91E-05	0	3.81E-06
8	32	419	0.0029474	60	4.40E-05	65	7.40E-05
9	72	589	4.79E-05	309	1.73E-08	43	1.01E-12
10	7	12	0.8125	14	1	1	0.03125
11	55	594	0.1414439	149	2.00E-07	78	6.88E-09
12	47	1010	3.02E-07	22	7.62E-12	197	4.89E-05
13	52	309	0.0005481	7	5.42E-10	0	3.61E-10
15	14	58	0.7608642	18	0.0295410	3	0.0006103
16	14	18	0.0295410	11	0.0067138	9	0.00402832
17	71	1486	0.23446291	398	4.67E-07	376	2.40E-07
18	38	565	0.0040431	8	1.82E-10	57	5.18E-07
19	16	133	0.0001525	0	3.05E-05	3	0.0001525
20	62	690	0.0449452	0	7.77E-12	24	2.48E-11
21	52	669	0.8590490	376	0.00442845	4	4.56E-10
22	53	1023	0.00657178	3	2.92E-10	139	3.41E-07
23	9	30	0.42578125	11	0.203125	4	0.02734375
24	50	545	0.3744860	3	9.35E-10	22	2.91E-09
25	43	8	5.68E-12	0	2.27E-13	0	2.27E-13
26	29	178	0.4046813	12	2.61E-07	7	7.08E-08
27	6	0	0.03125	0	0.03125	0	0.03125
28	12	0	0.0004882	0	0.0004882	0	0.0004882
29	21	185	0.0141658	0	9.54E-07	85	0.3038158
30	44	850	1.11E-05	137	9.02E-06	54	5.80E-09
31	48	18	1.80E-12	0	7.11E-15	65	1.25E-09
32	68	224	6.80E-09	10	1.22E-12	25	2.36E-12
33	18	66	0.4171142	4	5.34E-05	16	0.0012893
34	34	351	0.3695251	0	1.16E-10	0	1.16E-10
35	46	59	2.58E-09	0	2.84E-14	0	2.84E-14
36	46	545	0.96548075	313	0.0121631	82	2.77E-08
37	11	0	0.0009765	2	0.0029296	1	0.0019531
38	19	190	3.81E-06	135	0.1133766	24	0.0028381

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
39	16	67	0.9799499	0	3.05E-05	19	0.0091857
41	51	668	0.9663547	34	3.83E-09	5	7.14E-10
42	42	719	0.0005558	3	2.27E-12	47	9.88E-09
43	10	45	0.0839843	24	0.76953125	2	0.0058593
44	62	1150	0.2251620	60	1.34E-10	21	2.15E-11
46	9	42	0.01953125	1	0.0078125	0	0.00390625
47	7	8	0.375	12	0.8125	0	0.015625
49	17	149	0.0001068	106	0.1742553	45	0.1454315
50	16	118	0.0076293	24	0.0213928	90	0.2744448
52	6	0	0.03125	1	0.0625	0	0.03125
53	47	865	0.0011072	471	0.3308335	198	5.16E-05
54	49	1136	6.74E-09	293	0.0011523	0	3.55E-15
57	17	3	7.63E-05	0	1.53E-05	0	1.53E-05
58	6	1	0.0625	5	0.3125	19	0.09375
59	17	135	0.0038452	16	0.0025787	16	0.0025787
60	37	98	5.14E-05	14	1.60E-09	26	1.56E-08
61	9	3	0.01953125	23	1	20	0.8203125
62	57	158	1.11E-07	31	2.68E-10	146	6.56E-08
63	9	28	0.5703125	2	0.01171875	0	0.00390625
64	35	93	0.0001282	79	3.80E-05	0	5.82E-11
66	31	457	7.01E-06	100	0.0029005	14	1.02E-07
67	8	2	0.0234375	29	0.1484375	20	0.84375
68	43	709	0.0037357	3	1.14E-12	109	2.24E-06
69	10	0	0.0019531	4	0.0136718	7	0.0371093
70	24	164	0.7047564	0	1.19E-07	2	3.58E-07
71	6	16	0.3125	14	0.5625	8	0.6875
72	29	296	0.0919583	63	0.0004513	0	3.73E-09
74	14	59	0.71484375	0	0.00012207	0	0.00012207
75	17	126	0.0174255	1	3.05E-05	0	1.53E-05
76	6	5	0.3125	0	0.03125	0	0.03125
77	41	21	4.07E-10	0	9.09E-13	8	2.27E-11
78	8	0	0.0078125	3	0.0390625	3	0.0390625
82	7	19	0.46875	17	0.6875	1	0.03125
83	54	140	2.18E-07	72	7.98E-09	0	1.67E-10
84	45	385	0.1372818	3	2.84E-13	113	7.94E-07
85	28	28	1.10E-05	0	7.45E-09	0	7.45E-09
86	49	88	6.15E-09	4	2.49E-14	1	7.11E-15
87	10	0	0.0019531	0	0.0019531	0	0.0019531
88	6	12	0.84375	2	0.09375	1	0.0625
90	22	1	9.54E-07	0	4.77E-07	0	4.77E-07
93	19	43	0.0360679	1	7.63E-06	0	3.81E-06
94	32	205	0.2781296	347	0.1240465	0	4.66E-10

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
95	6	15	0.4375	0	0.03125	0	0.03125
96	14	38	0.3909912	18	0.0295410	2	0.0003662
98	6	3	0.15625	9	0.84375	0	0.03125
101	12	19	0.1293945	0	0.0004882	17	0.0922851
104	42	3	2.27E-12	0	4.55E-13	0	4.55E-13
105	50	0	7.79E-10	50	1.46E-08	606	0.7647480
106	8	1	0.015625	0	0.0078125	0	0.0078125
107	41	49	2.53E-08	0	9.09E-13	0	9.09E-13
108	25	138	0.5249125	0	5.96E-08	0	5.96E-08
109	8	0	0.0078125	5	0.078125	14	0.640625
110	22	0	4.77E-07	1	9.54E-07	0	4.77E-07
111	8	19	0.9453125	0	0.0078125	0	0.0078125
113	14	93	0.0085449	13	0.0107421	71	0.2675781
114	8	4	0.0546875	0	0.0078125	7	0.1484375
115	6	11	1	15	0.4375	5	0.3125
116	36	72	9.93E-06	0	2.91E-11	0	2.91E-11
117	25	38	0.0003764	16	1.01E-05	16	1.01E-05
118	28	77	0.0031605	25	6.74E-06	0	7.45E-09
119	33	102	0.0009519	0	2.33E-10	0	2.33E-10
120	17	118	0.0505371	0	1.53E-05	13	0.0013427
121	29	4	2.61E-08	0	3.73E-09	0	3.73E-09
122	18	14	0.0008392	11	0.0004196	0	7.63E-06
125	41	13	8.00E-11	24	6.93E-10	0	9.09E-13
126	14	89	0.0202636	53	1	1	0.0002441
129	9	2	0.01171875	4	0.02734375	0	0.00390625
130	6	15	0.4375	3	0.15625	0	0.03125
131	20	69	0.1893482	0	1.91E-06	0	1.91E-06
132	38	178	0.0044696	0	7.28E-12	9	2.40E-10
139	34	14	1.28E-08	6	1.63E-09	53	5.14E-06
140	22	50	0.0114727	25	0.0004282	6	6.68E-06
141	51	17	1.44E-09	26	2.43E-09	75	3.65E-08

APPENDIX E

Results of the Mann-Whitney-Wilcoxon test comparing 1:50 000 contour section slopes with DEM20, DEM90 and DEM200 -derived slopes for 109 river profiles in the X catchment
(n = sample size)

REACH NUM	n	Total sum of ranks	DEM20		DEM90		DEM200	
			V	p	V	p	V	p
1	104	5460	3087	0.247656	2882	0.623225	3302	0.063844
2	104	5460	2673	0.854626	3010	0.364743	3136	0.188524
4	15	120	55	0.803955	74	0.454285	84	0.187622
5	48	1176	537	0.607569	576	0.906974	662	0.454385
6	56	1596	835	0.765907	840	0.734972	802	0.977224
7	18	171	64	0.369217	82	0.898575	85	1.000000
8	31	496	257	0.869576	231	0.749841	290	0.421377
9	71	2556	1383	0.549328	1522	0.162951	1512	0.180924
10	6	21	12	0.843750	12	0.843750	14	0.562500
11	54	1485	726	0.890427	814	0.540984	865	0.293513
12	46	1081	507	0.720958	607	0.474459	590	0.595682
13	51	1326	711	0.656147	694	0.774962	790	0.235724
15	13	91	29	0.273438	57	0.454834	48	0.892578
16	13	91	49	0.839355	66	0.167725	49	0.839355
17	70	2485	1121	0.478874	1273	0.860635	1136	0.535040
18	37	703	312	0.560531	328	0.731629	455	0.121123
19	15	120	40	0.276855	68	0.678772	43	0.359131
20	61	1891	765	0.196046	874	0.610068	993	0.735672
21	51	1326	618	0.676591	751	0.412114	652	0.921598
22	52	1378	730	0.712254	662	0.809297	880	0.082764
23	8	36	20	0.843750	25	0.382813	21	0.742188
24	49	1225	558	0.594236	756	0.156153	719	0.294512
25	42	903	442	0.911346	467	0.852773	537	0.291127
26	28	406	185	0.694702	204	0.991060	263	0.178234
27	5	15	8	1.000000	5	0.625000	9	0.812500
28	11	66	43	0.413086	43	0.413086	23	0.413086
29	20	210	119	0.621513	98	0.812355	157	0.053169
30	43	946	525	0.537762	526	0.529874	626	0.065181
31	47	1128	627	0.511836	627	0.511836	734	0.072663
32	67	2278	1253	0.478328	1238	0.538360	1303	0.307100
33	17	153	67	0.677704	89	0.579056	69	0.746658
34	33	561	284	0.957828	287	0.915770	283	0.971878
35	45	1035	452	0.466816	510	0.937646	643	0.159694
36	45	1035	519	0.991083	572	0.545712	651	0.134285
37	10	55	31	0.769531	41	0.193359	26	0.921875
38	18	171	97	0.639694	104	0.442299	93	0.766029

REACH NUM	n	Total sum of ranks	DEM20		DEM90		DEM200	
			V	p	V	p	V	p
39	15	120	83	0.207764	58	0.934082	81	0.252380
41	50	1275	704	0.524049	755	0.258715	732	0.364191
42	41	861	474	0.581124	459	0.719560	538	0.167290
43	9	45	14	0.359375	27	0.652344	24	0.910156
44	61	1891	1002	0.687511	1076	0.350427	1202	0.065946
46	8	36	14	0.640625	24	0.460938	9	0.250000
47	6	21	6	0.437500	4	0.218750	5	0.312500
49	16	136	71	0.899933	67	0.979950	53	0.463745
50	15	120	76	0.389404	64	0.846924	91	0.083252
52	5	15	8	1.000000	7	1.000000	10	0.625000
53	46	1081	688	0.108768	661	0.191729	710	0.064469
54	48	1176	660	0.466798	661	0.460569	866	**0.003780**
57	16	136	65	0.899933	68	1.000000	88	0.322510
58	5	15	12	0.312500	13	0.187500	10	0.625000
59	16	136	40	0.159058	62	0.781952	64	0.860260
60	36	666	407	0.251545	363	0.646873	413	0.214469
61	8	36	23	0.546875	21	0.742188	23	0.546875
62	56	1596	950	0.216534	1062	**0.031603**	1077	**0.023102**
63	8	36	10	0.312500	18	1.000000	13	0.546875
64	34	595	342	0.456777	307	0.879293	340	0.477588
66	30	465	239	0.903226	252	0.700033	273	0.416130
67	7	28	20	0.375000	25	0.078125	20	0.375000
68	42	903	514	0.442144	493	0.611694	641	**0.017008**
69	9	45	28	0.570313	21	0.910156	20	0.820313
70	23	276	131	0.846232	146	0.822927	162	0.481952
71	5	15	13	0.187500	10	0.625000	9	0.812500
72	28	406	190	0.779298	247	0.327210	237	0.451477
74	13	91	30	0.305420	50	0.786865	50	0.786865
75	16	136	48	0.322510	60	0.705719	51	0.403748
76	5	15	4	0.437500	9	0.812500	7	1.000000
77	40	820	373	0.627285	522	0.135084	458	0.527213
78	7	28	16	0.812500	17	0.687500	15	0.937500
82	6	21	7	0.562500	6	0.437500	12	0.843750
83	53	1431	827	0.325776	712	0.978812	904	0.096049
84	44	990	374	0.161137	390	0.225067	531	0.681575
85	27	378	207	0.678951	211	0.610933	220	0.469840
86	48	1176	612	0.811241	670	0.406604	707	0.226452
87	9	45	26	0.734375	24	0.910156	17	0.570313
88	5	15	7	1.000000	15	0.062500	8	1.000000
90	21	231	100	0.609149	111	0.891732	127	0.707934
93	18	171	85	1.000000	103	0.468292	98	0.609459
94	31	496	262	0.794220	343	0.063469	318	0.175666

REACH NUM	n	Total sum of ranks	DEM20		DEM90		DEM200	
			V	p	V	p	V	p
95	5	15	5	0.625000	11	0.437500	8	1.000000
96	13	91	33	0.414307	48	0.892578	50	0.786865
98	5	15	10	0.625000	11	0.437500	7	1.000000
101	11	66	45	0.320313	39	0.637695	46	0.278320
104	41	861	621	**0.012707**	588	**0.041018**	577	0.057950
105	49	1225	652	0.700552	735	0.227113	826	**0.033266**
106	7	28	6	0.218750	12	0.812500	14	1.000000
107	40	820	398	0.878507	470	0.427972	527	0.118149
108	24	300	172	0.545670	169	0.603311	171	0.564589
109	7	28	18	0.578125	18	0.578125	13	0.937500
110	21	231	110	0.864887	90	0.392584	113	0.945745
111	7	28	18	0.578125	23	0.156250	14	1.000000
113	13	91	48	0.892578	49	0.839355	79	**0.017090**
114	7	28	5	0.156250	13	0.937500	19	0.468750
115	5	15	0	0.062500	6	0.812500	9	0.812500
116	35	630	327	0.852456	362	0.451014	418	0.093448
117	24	300	135	0.683986	203	0.135528	228	**0.024864**
118	27	378	202	0.767608	205	0.713978	187	0.971726
119	32	528	268	0.948544	256	0.890003	317	0.330925
120	16	136	70	0.939880	84	0.433197	87	0.348389
121	28	406	222	0.678179	233	0.507584	245	0.350163
122	17	153	70	0.781906	101	0.263321	103	0.224686
125	40	820	441	0.685016	486	0.313807	549	0.062184
126	13	91	40	0.735352	59	0.375732	51	0.735352
129	8	36	21	0.742188	23	0.546875	25	0.382813
130	5	15	7	1.000000	5	0.625000	5	0.625000
131	19	190	79	0.541218	105	0.708557	109	0.594887
132	37	703	422	0.294686	460	0.103749	415	0.346034
139	33	561	316	0.536590	359	0.165498	438	**0.004023**
140	21	231	112	0.918694	140	0.411982	134	0.539189
141	50	1275	701	0.543084	803	0.111207	966	**0.001544**

APPENDIX F

Results of the Mann-Whitney-Wilcoxon test comparing contour elevations derived at 100m horizontal distance intervals with DEM20, DEM90 and DEM200 –derived elevations, for 109 river profiles in the X catchment (n = sample size)

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
1	3321	4170571	4.18E-144	2810397	0.343871	1712441	7.46E-80
2	1849	611280	2.37E-26	455744	8.93E-68	505532	2.34E-52
4	1326	167707	7.92E-85	287871	1.14E-27	276794	1.35E-31
5	349	9695	2.19E-28	3340	3.92E-47	6624	7.82E-37
6	1139	565388	2.95E-104	89204	9.46E-100	93335	2.39E-96
7	807	26112	6.81E-95	1498	2.58E-131	0	1.00E-133
8	699	43149	1.01E-49	18091	7.85E-85	5646	8.23E-106
9	1181	219171	1.70E-28	324268	0.035004	181879	4.24E-46
10	191	1240	3.66E-25	5175	1.80E-07	26	6.52E-33
11	665	26746	2.12E-64	107	2.39E-110	10715	1.50E-90
12	649	42750	2.39E-39	2132	1.05E-103	66895	6.96E-16
13	658	54261	1.26E-28	1277	6.74E-107	0	2.05E-109
15	599	32969	4.40E-41	11443	1.93E-76	21599	2.28E-58
16	581	10023	1.15E-75	24723	2.09E-49	49254	2.89E-18
17	1063	103878	2.14E-71	8689	5.54E-165	35881	2.99E-134
18	590	92727	0.179983	18471	8.90E-62	44826	1.57E-24
19	496	2812	9.71E-76	0	5.71E-83	8325	1.55E-62
20	532	41423	9.85E-17	0	7.56E-89	478	1.11E-87
21	520	24904	8.17E-36	2306	3.36E-81	1284	1.07E-83
22	361	13768	1.63E-21	30	8.32E-61	775	3.82E-58
23	450	27315	2.15E-17	13314	7.13E-42	10948	4.17E-47
24	462	28708	6.35E-18	61	3.03E-77	3545	9.87E-68
25	686	17829	1.23E-82	0	5.53E-114	5254	3.25E-104
26	428	14507	1.46E-34	9477	6.36E-46	368	9.57E-71
27	398	23387	1.21E-12	5704	1.38E-49	1971	1.18E-60
28	419	0	2.15E-70	0	2.15E-70	0	2.15E-70
29	445	7683	7.72E-54	58	1.80E-74	5841	1.65E-58
30	406	26287	2.16E-10	1237	2.38E-64	1947	3.73E-62
31	415	21649	1.39E-18	0	9.70E-70	14080	1.27E-32
32	414	41690	0.604430	548	7.37E-68	10157	2.61E-41
33	397	2726	3.85E-58	106	1.89E-66	34402	0.025827
34	262	12215	4.47E-05	259	1.94E-43	39	1.58E-44
35	142	2550	2.69E-07	0	4.80E-25	0	4.80E-25
36	399	32972	0.002653	18651	3.02E-20	14035	3.23E-29
37	362	331	6.86E-60	1416	4.43E-56	219	2.73E-60
38	379	60414	2.73E-30	46733	4.99E-07	13360	2.66E-26

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
39	367	3278	8.55E-51	583	7.72E-60	1131	6.14E-58
41	475	31994	2.50E-16	119	3.26E-79	74	2.45E-79
42	306	24840	0.382060	0	6.38E-52	2584	1.72E-41
43	354	3487	1.29E-47	24753	0.000543	464	4.52E-58
44	481	37744	3.40E-11	23366	8.11E-30	692	1.18E-78
46	327	967	1.46E-51	0	2.35E-55	63	4.19E-55
47	266	948	7.66E-41	15138	0.037181	0	2.24E-45
49	307	24607	0.534239	21312	0.135017	23568	0.963875
50	188	1271	2.24E-24	1071	1.38E-25	3662	2.79E-12
52	293	11660	1.02E-11	636	5.32E-47	0	8.54E-50
53	318	39775	1.57E-18	20711	0.004608	18578	3.58E-05
54	313	18987	0.00	1290	8.01E-48	0	4.57E-53
57	131	183	1.92E-21	0	3.09E-23	0	3.09E-23
58	242	470	5.99E-39	5062	9.39E-19	21344	1.11E-09
59	289	10984	2.38E-12	2484	1.43E-38	2122	4.99E-40
60	274	6793	4.57E-20	811	6.69E-43	2427	7.53E-36
61	243	16	1.59E-41	13565	0.25	9678	2.73E-06
62	225	489	7.10E-36	75	3.15E-38	0	1.16E-38
63	248	2454	1.64E-30	358	1.45E-40	4	2.08E-42
64	238	13867	0.74	1999	1.42E-30	263	2.32E-39
66	237	18371	5.34E-05	1963	1.52E-30	252	2.99E-39
67	233	3	5.88E-40	23716	1.23E-22	12222	0.17
68	235	5217	1.14E-16	17	3.31E-40	8483	2.49E-07
69	194	1377	5.80E-25	1729	5.66E-23	10434	0.21
70	222	16323	3.81E-05	0	3.59E-38	556	5.72E-35
71	207	82	3.38E-35	18337	1.69E-18	8748	0.02
72	221	11869	0.68	2131	1.76E-26	56	1.12E-37
74	190	2118	5.10E-20	0	6.31E-33	0	6.31E-33
75	184	3377	1.30E-12	37	1.11E-31	0	6.09E-32
76	203	1928	8.92E-24	0	4.66E-35	0	4.66E-35
77	187	136	1.72E-31	0	1.96E-32	431	1.72E-29
78	192	14	3.69E-33	5606	2.10E-06	237	1.17E-31
82	193	673	5.11E-29	15587	1.12E-15	603	1.84E-29
83	192	8913	0.65	280	2.25E-31	5	3.21E-33
84	189	4133	1.25E-10	4	9.82E-33	913	9.28E-27
85	183	175	1.54E-30	0	8.88E-32	0	8.88E-32
86	184	6110	0.0009106	15	7.78E-32	10	7.17E-32
87	158	620	8.72E-23	0	1.13E-27	0	1.13E-27
88	183	993	4.33E-25	1688	6.71E-21	124	6.74E-31
90	157	33	3.09E-27	0	1.64E-27	0	1.64E-27
93	163	189	5.34E-27	39	3.49E-28	0	1.70E-28
94	163	1582	2.88E-17	3248	1.26E-08	0	1.70E-28

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
95	153	100	5.27E-26	21	1.13E-26	82	3.72E-26
96	171	667	6.24E-25	588	1.74E-25	57	2.25E-29
98	125	17	4.52E-22	4812	0.03	9	3.73E-22
101	142	191	2.57E-23	0	4.80E-25	279	1.53E-22
104	143	3	3.50E-25	0	3.28E-25	0	3.28E-25
105	144	96	1.65E-24	11	2.83E-25	1206	1.20E-15
106	131	200	2.79E-21	0	3.09E-23	28	5.88E-23
107	132	389	1.05E-19	0	2.11E-23	0	2.11E-23
108	129	807	1.76E-15	0	6.59E-23	0	6.59E-23
109	362	3	4.56E-61	8950	3.72E-33	42170	2.91E-06
110	131	33	6.59E-23	12	4.07E-23	0	3.09E-23
111	114	80	1.58E-19	0	1.94E-20	0	1.94E-20
113	105	1167	2.43E-07	375	1.42E-14	1210	5.02E-07
114	105	61	3.36E-18	6	7.03E-19	725	4.84E-11
115	104	1408	1.82E-05	5039	7.10E-14	1254	1.71E-06
116	105	1	6.09E-19	0	5.92E-19	0	5.92E-19
117	99	555	2.09E-11	106	1.38E-16	8	7.38E-18
118	96	182	4.49E-15	31	4.77E-17	0	1.81E-17
119	96	217	1.23E-14	0	1.81E-17	0	1.81E-17
120	66	1184	0.62	0	1.68E-12	43	1.17E-11
121	81	149	1.13E-12	0	5.46E-15	0	5.46E-15
122	84	539	2.78E-08	53	1.14E-14	0	1.74E-15
125	69	9	7.91E-13	16	1.07E-12	0	5.33E-13
126	59	1062	0.18	293	8.02E-06	3	2.86E-11
129	186	6	3.15E-32	4140	5.82E-10	0	2.86E-32
130	113	2165	0.0025077	2799	0.23	334	1.36E-16
131	81	96	1.79E-13	0	5.46E-15	0	5.46E-15
132	97	421	2.00E-12	0	1.24E-17	114	3.98E-16
139	43	27	2.87E-10	0	2.27E-13	25	2.06E-10
140	163	3119	3.53E-09	517	1.68E-24	863	5.27E-22
141	101	1434	0.0001110	59	1.55E-17	230	1.96E-15

APPENDIX G

Results of the Mann-Whitney-Wilcoxon test comparing contour elevations derived at 200m horizontal distance intervals with DEM20, DEM90 and DEM200 –derived elevations, for 109 river profiles in the X catchment (n = sample size)

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
1	1659	1039411	2.69E-72	747704	0.002410	427959	1.19E-40
2	926	153660	7.12E-14	120516	6.82E-31	127321	8.12E-27
4	664	42008	1.71E-43	78659	1.39E-10	69854	2.45E-16
5	239	3870	1.31E-22	1159	7.18E-35	3323	7.33E-25
6	571	142251	2.83E-53	26419	1.46E-44	23369	2.03E-49
7	405	6583	1.42E-48	556	2.52E-66	0	4.18E-68
8	351	10901	8.10E-26	5520	1.46E-40	1433	4.52E-54
9	592	55433	8.13E-15	86064	0.683122	45787	6.61E-24
10	97	364	4.50E-13	1452	0.000885	8	1.59E-17
11	293	10629	5.75E-14	154	4.13E-49	2416	1.28E-39
12	326	10664	6.20E-21	612	9.08E-53	16960	1.27E-08
13	331	13609	1.77E-15	379	1.59E-54	0	5.20E-56
15	301	8410	2.74E-21	3353	1.29E-37	5443	2.78E-30
16	292	2576	8.58E-39	7695	2.49E-21	12317	3.35E-10
17	533	26277	1.72E-36	2659	1.27E-82	9217	6.70E-68
18	297	23632	0.309625	5032	8.30E-31	11413	4.75E-13
19	249	668	3.67E-39	0	1.36E-42	2121	3.28E-32
20	267	10481	4.49E-09	0	1.53E-45	138	7.23E-45
21	261	6170	3.57E-19	491	3.91E-42	292	4.15E-43
22	182	3660	5.52E-11	25	1.96E-31	339	3.17E-29
23	226	6850	1.26E-09	3867	8.76E-20	2756	1.42E-24
24	232	7157	5.26E-10	27	1.17E-39	902	6.79E-35
25	344	4522	2.89E-42	0	3.90E-58	1321	3.13E-53
26	215	3729	6.17E-18	3283	7.68E-20	215	9.95E-36
27	200	5896	4.02E-07	1565	4.08E-25	492	2.00E-31
28	211	0	2.28E-36	0	2.28E-36	0	2.28E-36
29	224	2164	6.13E-27	125	8.98E-38	1580	7.57E-30
30	204	6631	5.92E-06	357	5.69E-33	505	4.63E-32
31	209	5504	4.19E-10	0	4.84E-36	3564	2.61E-17
32	208	10535	0.702030	175	8.72E-35	2519	7.54E-22
33	200	743	6.96E-30	28	2.20E-34	8738	0.109542
34	137	3351	0.003135	98	2.70E-23	16	4.53E-24
35	72	634	0.000137	0	1.69E-13	0	1.69E-13
36	201	8505	0.046343	5318	4.86E-09	3654	3.62E-15
37	182	92	5.89E-31	357	4.22E-29	60	3.49E-31
38	191	15436	2.55E-16	12187	7.95E-05	3557	2.23E-13

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
39	185	878	3.30E-26	202	1.08E-30	388	2.01E-29
41	239	8008	3.27E-09	121	2.69E-40	21	7.67E-41
42	154	6298	0.551663	0	5.12E-27	639	7.19E-22
43	178	863	5.96E-25	7081	0.199119	126	4.87E-30
44	242	9672	3.96E-06	6467	4.24E-14	226	3.09E-40
46	165	279	1.18E-26	0	7.99E-29	17	1.09E-28
47	169	1404	1.19E-19	8969	0.005053	0	1.76E-29
49	155	6326	0.616296	5849	0.726897	5981	0.909681
50	95	341	6.23E-13	305	2.32E-13	1010	2.45E-06
52	148	2992	1.40E-06	185	2.02E-24	0	4.95E-26
53	164	10627	2.30E-10	5816	0.119392	4663	0.000560
54	162	4963	0.006159	304	6.25E-26	0	2.48E-28
57	67	59	1.55E-11	0	1.15E-12	0	1.15E-12
58	152	335	6.95E-24	1994	2.13E-12	6346	0.328238
59	146	2854	9.32E-07	779	3.27E-19	606	1.44E-20
60	138	1704	5.06E-11	289	1.00E-21	623	7.53E-19
61	123	9	7.98E-22	3665	0.709674	2449	0.000578
62	114	229	6.82E-18	36	5.02E-20	114	3.79E-19
63	125	728	2.64E-15	231	6.77E-20	1	3.07E-22
64	120	3543	0.820788	549	7.18E-16	74	1.26E-20
66	120	4581	0.012802	549	7.18E-16	61	9.15E-21
67	118	2	4.49E-21	6149	1.40E-12	3140	0.320410
68	120	1510	2.85E-08	9	2.50E-21	2256	0.000322
69	98	434	1.72E-12	471	4.39E-12	2639	0.450380
70	112	4206	0.002498	1	4.27E-20	151	2.22E-18
71	105	24	1.18E-18	4748	3.35E-10	2249	0.088400
72	112	3101	0.856018	694	7.54E-13	87	4.20E-19
74	96	547	7.69E-11	0	1.81E-17	0	1.81E-17
75	93	873	4.98E-07	12	8.36E-17	0	5.66E-17
76	103	494	6.79E-13	0	1.27E-18	0	1.27E-18
77	95	58	1.64E-16	0	2.65E-17	106	7.16E-16
78	97	7	1.54E-17	1499	0.001601	56	6.95E-17
82	99	243	6.78E-15	4254	5.38E-10	161	6.76E-16
83	97	2324	0.851576	71	1.10E-16	2	1.32E-17
84	96	1106	8.05E-06	2	1.93E-17	238	2.25E-14
85	93	126	3.04E-15	0	5.66E-17	0	5.66E-17
86	93	1580	0.020443	59	3.76E-16	13	8.63E-17
87	80	177	4.56E-12	0	8.00E-15	0	8.00E-15
88	91	253	3.32E-13	457	9.60E-11	35	3.84E-16
90	80	6	1.00E-14	0	8.00E-15	0	8.00E-15
93	83	72	3.34E-14	5	3.06E-15	0	2.55E-15
94	88	523	2.39E-09	982	4.93E-05	0	3.80E-16

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
95	78	33	6.10E-14	9	2.43E-14	22	4.01E-14
96	87	226	9.19E-13	246	1.70E-12	39	2.13E-15
98	64	7	5.03E-12	1389	0.019775	6	4.79E-12
101	72	72	3.24E-12	0	1.69E-13	92	7.15E-12
104	73	1	1.21E-13	0	1.16E-13	0	1.16E-13
105	74	26	2.27E-13	4	9.30E-14	373	4.69E-08
106	67	91	6.02E-11	2	1.25E-12	9	1.72E-12
107	67	161	1.02E-09	0	1.15E-12	1	1.20E-12
108	66	259	6.51E-08	0	1.68E-12	0	1.68E-12
109	155	0	3.50E-27	2596	7.24E-10	10087	5.20E-13
110	67	10	1.80E-12	7	1.57E-12	0	1.15E-12
111	58	29	1.60E-10	0	3.60E-11	0	3.60E-11
113	54	335	0.000458	129	1.31E-07	352	0.000785
114	54	27	7.45E-10	1	1.77E-10	223	7.87E-06
115	53	362	0.001778	1306	1.76E-07	326	0.000574
116	54	0	1.67E-10	0	1.67E-10	0	1.67E-10
117	51	161	2.59E-06	27	2.57E-09	21	1.82E-09
118	49	50	1.12E-10	12	2.49E-13	0	3.55E-15
119	51	87	6.87E-08	0	5.30E-10	0	5.30E-10
120	34	326	0.636298	0	1.16E-10	12	8.15E-09
121	42	74	2.00E-07	11	2.50E-11	0	4.55E-13
122	45	158	1.85E-05	0	5.68E-14	0	5.68E-14
125	38	76	3.76E-06	11	4.00E-10	0	7.28E-12
126	31	291	0.410205	71	0.000261	1	1.86E-09
129	94	4	4.40E-17	1110	2.33E-05	0	3.87E-17
130	58	591	0.040956	823	0.804324	90	3.16E-09
131	42	39	3.45E-09	0	4.55E-13	0	4.55E-13
132	52	175	2.92E-06	3	4.30E-10	54	7.54E-09
139	23	11	1.31E-05	0	2.38E-07	13	2.10E-05
140	83	846	4.70E-05	129	2.38E-13	224	5.42E-12
141	52	381	0.005104	16	9.10E-10	73	2.08E-08

APPENDIX H

Results of the Mann-Whitney-Wilcoxon test comparing contour elevations derived at 300m horizontal distance intervals with DEM20, DEM90 and DEM200 –derived elevations, for 109 river profiles in the X catchment (n = sample size)

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
1	1109	464784	4.82E-49	313911	0.563476	191267	9.43E-28
2	618	68508	1.00E-09	51679	4.20E-23	57022	3.44E-18
4	444	19218	6.80E-29	32591	5.25E-10	31407	2.95E-11
5	118	1106	1.08E-10	384	4.67E-17	755	1.38E-13
6	381	63396	3.65E-36	9892	7.40E-35	10526	2.74E-33
7	271	2950	4.26E-33	171	2.25E-45	0	3.40E-46
8	235	4989	1.78E-17	2113	1.97E-29	731	2.43E-36
9	395	24268	6.39E-11	36335	0.222558	20378	1.62E-16
10	65	176	4.76E-09	587	0.001527	4	2.97E-12
11	223	2987	6.88E-23	8	2.74E-38	1202	1.27E-31
12	218	4851	3.01E-14	276	7.03E-36	7628	3.85E-06
13	221	5928	2.76E-11	158	4.44E-37	0	5.23E-38
15	201	3702	5.76E-15	1301	8.47E-27	2440	9.86E-21
16	195	1179	2.56E-26	2919	4.13E-17	5508	2.93E-07
17	356	11445	1.30E-25	943	1.09E-56	4142	6.91E-46
18	198	10430	0.473261	2129	1.14E-21	5067	3.13E-09
19	167	377	2.83E-26	0	3.75E-29	988	6.05E-22
20	179	4663	1.03E-06	0	4.02E-31	63	1.16E-30
21	175	2912	9.80E-13	480	5.50E-27	171	3.36E-29
22	122	1764	3.84E-07	8	1.14E-21	123	1.87E-20
23	152	3072	4.59E-07	1467	1.29E-15	1236	3.76E-17
24	156	3482	2.98E-06	3	2.54E-27	439	8.62E-24
25	230	2034	8.55E-29	0	1.76E-39	584	3.10E-36
26	144	1786	7.52E-12	1115	2.71E-16	51	6.51E-25
27	134	2656	3.41E-05	680	1.43E-17	213	1.07E-21
28	141	0	7.00E-25	0	7.00E-25	0	7.00E-25
29	150	904	4.37E-19	4	2.52E-26	725	1.99E-20
30	137	3022	0.000251	146	7.55E-23	270	1.03E-21
31	140	2430	1.89E-07	0	1.02E-24	1569	2.55E-12
32	140	4740	0.685790	59	3.62E-24	1149	3.43E-15
33	134	296	6.28E-21	12	1.30E-23	3858	0.140316
34	89	1470	0.029512	49	1.35E-15	6	3.18E-16
35	49	313	0.002420	0	3.55E-15	0	3.55E-15
36	135	3780	0.075424	2096	4.34E-08	1592	4.60E-11
37	122	42	2.63E-21	152	3.74E-20	36	2.27E-21
38	128	6964	1.55E-11	5372	0.003104	1595	1.72E-09

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
39	124	438	1.04E-17	93	4.11E-21	185	3.57E-20
41	160	3712	3.37E-06	16	7.15E-28	9	6.27E-28
42	104	3089	0.245013	0	8.65E-19	297	3.07E-15
43	120	448	7.95E-17	2760	0.022780	58	8.50E-21
44	162	4375	0.000197	2663	4.53E-11	59	7.41E-28
46	111	119	1.46E-18	0	6.07E-20	9	7.75E-20
47	90	113	7.15E-15	1705	0.168790	0	1.77E-16
49	104	2915	0.549641	2479	0.416606	2710	0.949580
50	64	182	9.78E-09	112	5.55E-10	474	0.000156
52	99	1332	6.67E-05	73	5.21E-17	0	5.78E-18
53	108	4629	2.39E-07	2339	0.064340	2034	0.005358
54	106	2213	0.049940	213	1.41E-16	0	4.05E-19
57	45	37	3.26E-10	0	5.68E-14	0	5.68E-14
58	82	54	2.66E-14	629	7.20E-07	2434	0.000714
59	98	1369	0.000183	384	4.74E-13	316	7.81E-14
60	93	791	9.23E-08	124	2.86E-15	269	2.11E-13
61	83	7	3.29E-15	1551	0.384608	1083	0.002751
62	77	91	8.11E-13	0	2.51E-14	0	2.51E-14
63	84	340	1.18E-10	28	4.74E-15	0	1.74E-15
64	81	1630	0.887674	213	9.57E-12	37	2.15E-14
66	81	2124	0.029262	244	2.61E-11	26	1.43E-14
67	79	0	1.17E-14	2728	2.05E-08	1403	0.388375
68	80	669	5.14E-06	0	8.00E-15	999	0.002919
69	66	174	2.73E-09	205	8.96E-09	1185	0.613799
70	76	1946	0.012487	0	3.68E-14	73	6.29E-13
71	71	20	5.79E-13	2150	5.93E-07	1016	0.134041
72	75	1345	0.674628	263	8.60E-10	19	1.16E-13
74	65	250	7.80E-08	0	2.46E-12	0	2.46E-12
75	63	399	3.10E-05	5	6.73E-12	0	5.29E-12
76	69	225	4.32E-09	0	5.33E-13	0	5.33E-13
77	64	14	6.98E-12	0	3.61E-12	48	3.34E-11
78	66	5	2.11E-12	674	0.005900	29	6.26E-12
82	66	98	1.25E-10	1811	6.68E-06	68	3.49E-11
83	66	1083	0.888235	17	3.65E-12	1	1.76E-12
84	65	461	6.53E-05	1	2.58E-12	97	1.87E-10
85	63	4	6.42E-12	0	5.29E-12	0	5.29E-12
86	63	764	0.095509	5	6.73E-12	4	6.42E-12
87	54	73	8.40E-09	0	1.67E-10	0	1.67E-10
88	63	119	1.18E-09	205	3.93E-08	13	9.86E-12
90	54	12	3.27E-10	0	1.67E-10	0	1.67E-10
93	56	44	7.93E-10	6	1.07E-10	0	7.76E-11
94	56	158	1.82E-07	371	0.000503	0	7.76E-11

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
95	53	29	1.26E-09	3	2.92E-10	13	5.14E-10
96	59	90	2.01E-09	127	1.08E-08	9	3.89E-11
98	43	2	6.82E-13	593	0.150368	3	1.14E-12
101	49	37	2.04E-11	0	3.55E-15	42	4.04E-11
104	49	0	3.55E-15	0	3.55E-15	0	3.55E-15
105	50	14	1.81E-09	0	7.79E-10	151	2.71E-06
106	45	32	1.57E-10	0	5.68E-14	5	5.68E-13
107	46	102	1.71E-06	0	3.64E-09	0	3.64E-09
108	45	85	1.08E-06	0	5.36E-09	0	5.36E-09
109	122	0	9.36E-22	989	1.70E-12	4754	0.010464
110	45	0	5.68E-14	3	2.84E-13	0	5.68E-14
111	40	36	5.16E-07	0	3.71E-08	0	3.71E-08
113	37	159	0.003772	29	1.19E-06	160	0.003958
114	37	19	5.48E-07	2	1.40E-07	105	0.000206
115	36	178	0.013927	608	2.30E-06	152	0.003692
116	37	0	1.19E-07	0	1.19E-07	0	1.19E-07
117	35	79	0.000115	12	7.24E-07	4	3.66E-07
118	34	31	5.42E-06	5	5.97E-07	0	3.82E-07
119	34	24	3.05E-06	0	3.82E-07	0	3.82E-07
120	24	189	0.271308	0	1.94E-05	5	3.65E-05
121	29	24	3.00E-05	0	2.70E-06	0	2.70E-06
122	30	72	0.000998	17	9.77E-06	0	1.82E-06
125	25	3	1.88E-05	1	1.48E-05	0	1.31E-05
126	21	119	0.918694	30	0.001859	1	1.91E-06
129	64	6	4.79E-12	477	0.000169	0	3.61E-12
130	39	256	0.061974	324	0.364720	44	5.38E-08
131	29	12	9.30E-06	0	2.70E-06	0	2.70E-06
132	34	80	8.13E-05	0	1.16E-10	31	2.76E-07
139	16	8	0.000763	0	3.05E-05	7	0.000580
140	56	362	0.000382	71	3.10E-09	93	9.10E-09
141	35	165	0.013025	7	1.11E-09	26	6.22E-08

APPENDIX I

Results of the Mann-Whitney-Wilcoxon test comparing contour elevations derived at 400m horizontal distance intervals with DEM20, DEM90 and DEM200 –derived elevations, for 109 river profiles in the X catchment (n = sample size)

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
1	832	261805	2.44E-37	176527	0.637994	107179	1.57E-21
2	464	38460	8.49E-08	28444	1.12E-18	32011	3.25E-14
4	333	10666	1.87E-22	18301	6.45E-08	17709	9.33E-09
5	89	565	4.12E-09	206	2.01E-13	408	6.96E-11
6	286	35714	1.93E-27	5592	1.51E-26	5890	1.45E-25
7	203	1723	7.23E-25	93	1.84E-34	0	4.66E-35
8	176	2794	1.62E-13	1284	7.41E-22	488	4.11E-27
9	297	13944	3.32E-08	20613	0.307061	11613	1.27E-12
10	49	111	4.45E-08	350	0.008321	3	1.78E-14
11	168	1714	1.51E-17	6	2.86E-29	666	2.29E-24
12	164	2789	6.70E-11	150	1.78E-27	4325	6.19E-05
13	166	3402	1.28E-08	85	2.54E-28	0	5.47E-29
15	151	2073	9.93E-12	692	7.05E-21	1367	4.70E-16
16	147	666	2.73E-20	1459	1.41E-14	3138	8.64E-06
17	267	6542	2.61E-19	573	8.83E-43	2386	1.24E-34
18	149	5950	0.492697	1190	7.90E-17	2862	2.42E-07
19	126	259	8.35E-20	0	2.05E-22	581	8.47E-17
20	135	2820	0.000102	0	6.79E-24	39	1.62E-23
21	132	1631	3.78E-10	191	1.52E-21	73	1.11E-22
22	92	991	7.89E-06	7	1.04E-16	94	1.71E-15
23	114	1754	1.66E-05	804	2.71E-12	682	2.18E-13
24	117	1597	4.59E-07	2	6.56E-21	220	1.53E-18
25	173	1247	1.80E-21	0	3.88E-30	354	1.60E-27
26	109	875	1.41E-10	611	5.45E-13	29	2.89E-19
27	101	1489	0.000234	338	3.51E-14	118	8.55E-17
28	106	0	4.05E-19	0	4.05E-19	0	4.05E-19
29	113	525	1.16E-14	8	3.52E-20	462	2.76E-15
30	103	1911	0.011678	114	3.35E-17	148	8.66E-17
31	105	1382	7.62E-06	0	5.92E-19	892	1.52E-09
32	105	2724	0.852904	62	3.46E-18	636	6.87E-12
33	101	232	2.07E-15	6	3.24E-18	2204	0.208821
34	67	838	0.060502	31	4.58E-12	2	1.25E-12
35	37	187	0.012131	0	1.46E-11	0	1.46E-11
36	101	2076	0.090946	1121	8.41E-07	912	1.76E-08
37	92	23	1.76E-16	112	3.00E-15	21	1.65E-16
38	96	3920	6.03E-09	3078	0.006164	928	3.15E-07

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
39	93	232	7.26E-14	42	2.19E-16	115	2.17E-15
41	120	1921	7.66E-06	13	2.77E-21	8	2.44E-21
42	78	1628	0.664778	0	1.72E-14	164	7.21E-12
43	90	231	2.73E-13	1676	0.135493	32	5.16E-16
44	122	2409	0.000606	1512	1.06E-08	76	6.02E-21
46	83	85	5.26E-14	0	2.55E-15	5	3.06E-15
47	68	63	1.21E-11	992	0.270062	0	7.81E-13
49	78	1631	0.653960	1386	0.443060	1536	0.984105
50	49	119	9.39E-07	78	1.08E-07	288	0.001269
52	75	771	0.000559	39	2.55E-13	0	5.39E-14
53	81	2619	6.47E-06	1388	0.200316	1190	0.026905
54	80	1280	0.103453	105	3.76E-13	0	8.00E-15
57	34	21	5.20E-08	0	1.16E-10	0	1.16E-10
58	62	31	3.46E-11	339	7.97E-06	1409	0.002455
59	74	759	0.000717	249	8.75E-10	208	2.13E-10
60	70	449	3.47E-06	93	1.77E-11	164	2.81E-10
61	62	3	8.99E-12	857	0.404102	626	0.014133
62	58	23	1.18E-10	16	8.26E-11	0	3.60E-11
63	64	224	4.93E-08	17	8.03E-12	0	3.61E-12
64	61	923	0.874440	105	1.60E-09	17	2.64E-11
66	61	1147	0.148813	147	9.93E-09	17	2.64E-11
67	60	0	1.67E-11	1555	2.50E-06	825	0.509983
68	60	355	3.81E-05	0	1.67E-11	593	0.017945
69	50	103	2.54E-07	120	6.01E-07	676	0.713750
70	57	1088	0.038107	0	5.28E-11	39	4.03E-10
71	53	9	4.10E-10	1181	3.85E-05	573	0.208720
72	57	815	0.930356	164	1.44E-07	15	1.17E-10
74	49	148	6.82E-07	0	3.55E-15	0	3.55E-15
75	48	231	0.000256	3	2.03E-09	0	1.68E-09
76	52	132	4.02E-07	0	3.61E-10	0	3.61E-10
77	48	20	2.64E-12	0	7.11E-15	33	2.28E-11
78	50	3	9.34E-10	383	0.014209	11	1.51E-09
82	50	58	2.28E-08	988	0.000728	39	7.80E-09
83	50	619	0.862054	0	7.79E-10	0	7.79E-10
84	49	282	0.000748	0	3.55E-15	53	1.61E-10
85	47	0	1.42E-14	0	1.42E-14	0	1.42E-14
86	48	437	0.122680	6	2.46E-09	3	2.03E-09
87	41	50	2.86E-08	0	9.09E-13	0	9.09E-13
88	47	70	4.24E-09	105	1.07E-07	11	7.82E-13
90	41	2	2.73E-12	0	9.09E-13	0	9.09E-13
93	42	16	7.69E-11	0	4.55E-13	0	4.55E-13
94	42	90	8.96E-07	217	0.002780	0	4.55E-13

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
95	40	11	1.00E-10	2	5.46E-12	4	1.27E-11
96	44	74	5.04E-08	77	6.78E-08	9	3.75E-12
98	33	7	4.42E-09	339	0.304337	3	1.16E-09
101	37	20	5.40E-09	0	1.46E-11	23	9.31E-09
104	37	0	1.46E-11	0	1.46E-11	0	1.46E-11
105	38	7	1.41E-07	2	9.45E-08	96	7.08E-05
106	34	20	4.32E-08	0	1.16E-10	2	3.49E-10
107	35	52	1.71E-05	0	2.59E-07	0	2.59E-07
108	34	72	3.85E-05	0	1.16E-10	0	1.16E-10
109	92	0	8.28E-17	536	4.38E-10	2674	0.037408
110	34	1	2.33E-10	2	3.49E-10	0	1.16E-10
111	30	16	3.15E-07	0	1.86E-09	0	1.86E-09
113	28	110	0.033681	29	1.29E-05	99	0.016728
114	28	10	3.20E-07	0	7.45E-09	62	0.000792
115	28	105	0.026399	374	0.000103	100	0.019588
116	28	0	7.45E-09	0	7.45E-09	0	7.45E-09
117	26	29	5.16E-05	15	4.08E-06	3	1.49E-07
118	26	23	0.000113	4	1.40E-05	0	8.80E-06
119	26	9	2.48E-05	0	8.80E-06	0	8.80E-06
120	18	94	0.733727	0	7.63E-06	5	7.63E-05
121	22	12	3.34E-05	0	4.77E-07	0	4.77E-07
122	23	42	0.003675	0	2.89E-05	0	2.89E-05
125	19	0	3.81E-06	2	1.14E-05	0	3.81E-06
126	16	83	0.463745	25	0.024963	1	6.10E-05
129	48	1	1.42E-14	273	0.000932	0	7.11E-15
130	30	181	0.298844	185	0.338742	27	2.35E-06
131	22	4	3.34E-06	0	4.77E-07	0	4.77E-07
132	26	45	0.000465	0	2.98E-08	26	3.19E-05
139	12	5	0.004883	0	0.000488	4	0.003418
140	42	221	0.003322	45	7.66E-09	60	4.59E-08
141	27	103	0.038534	4	1.04E-07	21	6.66E-06

APPENDIX J

Results of the Mann-Whitney-Wilcoxon test comparing contour elevations derived at 500m horizontal distance intervals with DEM20, DEM90 and DEM200 –derived elevations, for 109 river profiles in the X catchment (n = sample size)

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
1	666	168016	1.93E-30	113000	0.695524	68828	1.88E-17
2	371	24496	1.29E-06	18552	1.19E-14	20473	1.14E-11
4	267	7026	7.92E-18	11883	1.98E-06	11382	2.58E-07
5	71	419	8.70E-07	149	1.01E-10	287	1.38E-08
6	229	22956	1.80E-22	3591	1.41E-21	3740	5.85E-21
7	163	1039	8.67E-21	73	6.52E-28	0	1.70E-28
8	141	1790	3.67E-11	729	1.36E-18	262	1.65E-22
9	238	9104	1.50E-06	12922	0.222173	7458	2.02E-10
10	40	81	1.54E-06	234	0.017158	2	5.46E-12
11	135	1088	1.47E-14	13	9.07E-24	439	7.82E-20
12	131	1876	1.91E-08	74	1.67E-22	2773	0.000371
13	133	2311	1.47E-06	37	3.34E-23	0	1.45E-23
15	121	1362	1.73E-09	502	1.64E-16	897	5.03E-13
16	118	415	9.45E-17	1056	4.40E-11	1979	3.93E-05
17	214	4089	2.98E-16	398	1.80E-34	1570	6.51E-28
18	120	3892	0.493448	785	9.38E-14	1873	4.22E-06
19	101	178	4.66E-16	0	2.71E-18	370	8.04E-14
20	108	1745	0.000242	0	1.90E-19	20	3.31E-19
21	106	1179	1.79E-07	184	6.51E-17	72	3.07E-18
22	74	619	0.000035	7	1.05E-13	63	9.84E-13
23	92	1118	0.000071	481	1.09E-10	430	2.88E-11
24	94	1237	0.000175	0	3.87E-17	151	4.25E-15
25	139	790	1.07E-17	0	1.49E-24	211	1.32E-22
26	87	596	2.46E-08	414	2.20E-10	18	1.04E-15
27	81	946	0.000775	267	5.43E-11	104	2.37E-13
28	85	0	1.19E-15	0	1.19E-15	0	1.19E-15
29	91	376	1.09E-11	5	1.43E-16	313	1.88E-12
30	83	1186	0.011518	4	2.95E-15	95	7.44E-14
31	85	887	0.000038	0	1.19E-15	574	4.01E-08
32	84	1686	0.660453	15	2.98E-15	414	9.83E-10
33	81	133	6.50E-13	5	6.58E-15	1415	0.248693
34	54	537	0.077548	20	5.08E-10	3	1.98E-10
35	30	155	0.114177	0	1.86E-09	0	1.86E-09
36	81	1287	0.079056	750	1.83E-05	564	2.47E-07
37	74	7	1.05E-13	89	2.70E-12	15	1.45E-13
38	77	2529	1.84E-07	1935	0.027910	621	7.89E-06

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
39	75	132	8.79E-12	18	1.11E-13	76	1.07E-12
41	97	1393	0.000405	12	1.80E-17	3	1.36E-17
42	63	938	0.634214	0	5.29E-12	107	7.05E-10
43	72	139	4.37E-11	939	0.035590	18	3.60E-13
44	98	1600	0.003462	1005	4.86E-07	18	1.47E-17
46	67	44	8.09E-12	0	1.15E-12	3	1.31E-12
47	55	45	1.28E-09	654	0.333183	0	1.14E-10
49	63	1066	0.693839	927	0.581557	984	0.872185
50	39	85	4.40E-06	48	8.94E-08	175	0.002129
52	60	486	0.001608	27	6.43E-11	0	1.67E-11
53	65	1675	8.35E-05	860	0.165928	730	0.025421
54	64	821	0.143955	93	2.46E-10	0	3.61E-12
57	28	18	1.88E-06	0	7.45E-09	0	7.45E-09
58	50	22	2.91E-09	241	0.000132	895	0.013105
59	59	477	0.002099	149	2.83E-08	110	5.04E-09
60	56	283	2.71E-05	61	1.88E-09	97	1.10E-08
61	50	0	7.79E-10	539	0.344138	408	0.027063
62	47	54	6.98E-08	0	2.48E-09	0	2.48E-09
63	51	140	9.70E-07	20	1.72E-09	1	5.63E-10
64	49	581	0.759881	102	2.11E-08	12	2.49E-13
66	49	763	0.136624	61	4.04E-10	8	8.88E-14
67	48	0	7.11E-15	1009	4.53E-06	523	0.511660
68	49	211	6.64E-05	4	1.47E-09	377	0.019407
69	40	89	3.19E-06	82	1.69E-06	434	0.754694
70	46	781	0.007861	0	2.84E-14	26	3.04E-11
71	43	3	1.14E-12	784	8.60E-05	359	0.172240
72	46	488	0.573318	121	7.47E-07	11	1.56E-12
74	40	99	3.00E-05	0	3.71E-08	0	3.71E-08
75	38	159	0.001640	1	1.46E-11	0	7.28E-12
76	42	82	4.32E-07	0	4.55E-13	0	4.55E-13
77	39	16	6.15E-10	0	3.64E-12	20	1.35E-09
78	40	2	5.46E-12	226	0.012512	18	4.60E-10
82	40	55	1.04E-07	653	0.000755	26	1.94E-09
83	40	395	0.847156	0	1.82E-12	0	1.82E-12
84	39	155	0.000707	0	3.64E-12	34	1.36E-08
85	38	13	6.40E-10	0	7.28E-12	0	7.28E-12
86	38	247	0.074247	4	5.09E-11	3	3.64E-11
87	33	29	4.05E-07	0	2.33E-10	0	2.33E-10
88	38	40	6.33E-08	70	2.08E-06	8	1.82E-10
90	33	4	1.63E-09	0	2.33E-10	0	2.33E-10
93	34	6	1.63E-09	0	1.16E-10	0	1.16E-10
94	34	73	4.24E-05	133	0.004074	0	1.16E-10

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
95	32	6	6.52E-09	1	9.31E-10	0	4.66E-10
96	36	62	3.56E-06	44	4.29E-07	6	4.07E-10
98	27	5	1.04E-05	214	0.556107	3	8.32E-06
101	30	13	1.64E-07	0	1.86E-09	17	3.86E-07
104	30	1	3.73E-09	0	1.86E-09	0	1.86E-09
105	30	7	3.54E-08	1	3.73E-09	72	0.000555
106	28	22	3.99E-06	0	7.45E-09	0	7.45E-09
107	28	48	0.000172	0	7.45E-09	0	7.45E-09
108	27	79	0.006998	0	1.49E-08	0	1.49E-08
109	74	0	7.89E-14	367	3.91E-08	1716	0.077226
110	28	1	1.49E-08	4	5.22E-08	0	7.45E-09
111	24	11	6.56E-06	0	1.19E-07	0	1.19E-07
113	23	47	0.005910	11	0.000119	67	0.032003
114	23	9	9.29E-05	0	2.89E-05	48	0.006483
115	22	64	0.042498	226	0.000593	59	0.027535
116	23	1	3.30E-05	0	2.89E-05	0	0.000029
117	21	27	0.001176	17	0.000197	3	0.000005
118	21	8	2.38E-05	4	6.68E-06	0	0.000001
119	21	27	0.001176	0	9.54E-07	0	0.000001
120	15	65	0.803955	0	6.10E-05	1	0.000122
121	18	5	7.63E-05	0	7.63E-06	0	0.000008
122	18	27	0.008965	0	7.63E-06	0	0.000008
125	15	0	6.10E-05	0	6.10E-05	0	0.000061
126	13	65	0.190918	16	0.039795	0	0.000244
129	39	2	1.09E-11	174	0.002021	0	3.64E-12
130	24	107	0.229190	129	0.564589	18	3.02E-05
131	18	23	0.004745	0	0.000008	0	7.63E-06
132	21	16	0.000161	0	0.000001	14	0.000105
139	10	7	0.037109	0	0.001953	2	0.005859
140	34	153	0.012474	22	6.24E-08	39	8.81E-07
141	22	81	0.146517	11	2.62E-05	19	0.000146

APPENDIX K

Results of the Mann-Whitney-Wilcoxon test comparing contour slopes derived at 100m horizontal distance intervals with DEM20, DEM90 and DEM200 –derived slopes, for 109 river profiles in the X catchment (n = sample size)

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
1	3320	3654430	1.97E-59	3564880	1.64E-48	3589697	2.01E-51
2	1848	1107421	2.57E-28	1093277	2.03E-25	1162107	4.67E-41
4	1325	605902	5.50E-33	583416	4.21E-25	607146	1.87E-33
5	348	34094	0.046992	31843	0.430825	33831	0.064845
6	1138	417846	2.71E-17	391942	9.21E-10	414826	2.70E-16
7	806	227240	1.44E-22	200585	9.28E-09	210121	6.68E-13
8	698	162048	5.50E-14	144715	1.98E-05	145047	1.50E-05
9	1180	435480	1.03E-13	433870	2.88E-13	398924	1.59E-05
10	190	11373	0.002443	11736	0.000451	12254	2.78E-05
11	664	139653	3.26E-09	132408	8.48E-06	132809	5.79E-06
12	648	130175	1.51E-07	120107	0.001691	132659	7.80E-09
13	657	141580	5.82E-12	131462	1.55E-06	131165	2.10E-06
15	598	114508	3.53E-09	109447	2.51E-06	110235	9.90E-07
16	580	108930	9.73E-10	106585	3.15E-08	103772	1.32E-06
17	1062	356725	9.23E-14	354763	4.01E-13	353210	1.25E-12
18	589	111607	2.16E-09	103534	5.55E-05	119569	2.53E-15
19	495	83636	2.75E-12	71303	0.001831	70855	0.002924
20	531	82782	0.000588	85891	1.59E-05	83946	0.000166
21	519	85796	8.26E-08	78125	0.001827	81507	4.02E-05
22	360	37254	0.015918	35513	0.126096	36242	0.057614
23	449	66453	6.85E-09	61013	0.000135	64062	8.44E-07
24	461	65879	1.01E-05	65156	3.16E-05	65418	2.11E-05
25	685	144691	1.50E-07	135906	0.000375	137768	9.00E-05
26	427	57713	2.45E-06	52907	0.004675	52512	0.007499
27	397	53953	2.67E-10	52521	1.27E-08	46952	0.001128
28	418	63157	4.58E-15	53663	6.43E-05	52518	0.000411
29	444	62109	2.61E-06	57445	0.002926	59304	0.000250
30	405	53304	2.29E-07	48316	0.002229	44150	0.196870
31	414	49097	0.011665	51706	0.000327	42608	0.887703
32	413	49799	0.003664	48732	0.013658	51301	0.000424
33	396	51142	2.05E-07	48426	6.27E-05	43830	0.047027
34	261	19459	0.052899	19066	0.106570	19970	0.018555
35	141	5501	0.308324	5265	0.594006	5573	0.243239
36	398	48988	5.25E-05	45869	0.007233	49457	0.000022
37	361	42364	1.03E-06	39662	0.000426	38189	0.005418
38	378	45012	1.52E-05	44702	2.91E-05	46912	0.000000

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
39	366	41789	5.07E-05	39217	0.005392	42363	0.000015
41	474	70856	1.05E-06	68197	6.57E-05	64260	0.007544
42	305	26936	0.019417	25278	0.207017	27876	0.003206
43	353	38825	0.000077	37363	0.001419	39864	0.000007
44	480	70798	1.70E-05	61917	0.167529	64519	0.025354
46	326	35062	7.86E-07	31684	0.003124	33648	0.000040
47	265	24150	1.73E-07	20932	0.008057	18569	0.448743
49	306	29795	4.64E-05	28290	0.001926	25954	0.111097
50	187	10306	0.040743	9448	0.374284	11040	0.002394
52	292	28523	7.80E-07	25450	0.004927	27231	0.000052
53	317	25506	0.852330	26306	0.499041	26796	0.329045
54	312	28045	0.022811	28349	0.013617	26284	0.241073
57	130	4697	0.307666	4379	0.778581	4451	0.653810
58	241	17945	0.001902	17980	0.001704	18841	0.000084
59	288	23627	0.046318	22731	0.174127	25280	0.001572
60	273	22132	0.008596	21182	0.057417	19925	0.348536
61	242	20060	0.000001	18130	0.001663	18442	0.000602
62	224	14607	0.038794	13427	0.394681	12913	0.747586
63	247	19150	0.000644	17479	0.054142	18040	0.015316
64	237	16055	0.064509	16222	0.044801	15830	0.101939
66	236	17265	0.001775	14613	0.548792	15714	0.099305
67	232	14333	0.423827	16809	0.001286	16088	0.011914
68	234	15903	0.037630	14468	0.487331	16409	0.010258
69	193	10944	0.041606	10911	0.046062	10995	0.035465
70	221	12952	0.470988	14176	0.044740	14468	0.020670
71	206	12354	0.048110	12146	0.082996	11954	0.131183
72	220	14012	0.049510	12935	0.409543	12477	0.733748
74	189	10388	0.061148	9811	0.268651	11084	0.005162
75	183	10041	0.023752	9025	0.397988	8916	0.488110
76	202	12675	0.003581	11236	0.236846	12385	0.010341
77	186	9442	0.310275	9329	0.389266	8572	0.867138
78	191	11778	0.000647	9926	0.322077	10582	0.064640
82	192	10690	0.064469	9941	0.380251	11619	0.002259
83	191	9851	0.372305	9614	0.560328	9370	0.792242
84	188	9053	0.820515	9317	0.561745	9560	0.365192
85	182	9798	0.038747	8523	0.783013	10438	0.003016
86	183	9466	0.144341	9574	0.107331	9132	0.320051
87	157	7277	0.059561	7094	0.117985	6273	0.900973
88	182	10788	0.000544	10230	0.007498	10031	0.016652
90	156	7286	0.039695	6242	0.833924	5946	0.754815
93	162	7543	0.115573	7259	0.271900	6283	0.594870
94	162	7407	0.178233	7574	0.104062	7871	0.033824

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
95	152	6561	0.169692	6734	0.090764	6229	0.445779
96	170	8295	0.110041	8091	0.200340	8195	0.149188
98	124	4614	0.065536	4767	0.026207	4052	0.659839
101	141	6294	0.008029	5544	0.268189	6072	0.028241
104	142	5539	0.346789	5413	0.493822	5203	0.797494
105	143	5624	0.337949	5732	0.239647	6405	0.011338
106	130	5310	0.014503	4781	0.224254	5124	0.044183
107	131	4755	0.321559	4920	0.170593	4791	0.282840
108	128	4528	0.342075	4182	0.898757	3577	0.190475
109	361	38783	0.002067	41789	0.000004	42018	0.000002
110	130	4678	0.329089	4105	0.723938	4628	0.389917
111	113	3538	0.363792	3432	0.545523	3382	0.644623
113	104	3068	0.273758	2956	0.464624	3998	0.000040
114	104	3219	0.113166	2754	0.939255	3077	0.261165
115	103	3110	0.155522	3045	0.227908	2519	0.601991
116	104	3020	0.347834	2867	0.658024	3251	0.091429
117	98	2688	0.353184	2491	0.817833	2575	0.597503
118	95	2547	0.322560	2659	0.160039	2365	0.753781
119	95	2580	0.266263	2240	0.883433	2322	0.877576
120	65	1082	0.953098	1226	0.317375	1245	0.260998
121	80	1611	0.967480	1632	0.956013	1628	0.971304
122	83	1997	0.249754	2076	0.131145	2128	0.080863
125	68	1170	0.987812	1205	0.847369	1283	0.503437
126	58	893	0.774521	842	0.919828	709	0.258315
129	185	9761	0.112340	10591	0.006414	10795	0.002651
130	112	3689	0.127820	3655	0.154447	2475	0.045629
131	80	1661	0.845980	1620	1	1504	0.579598
132	96	2481	0.577334	2603	0.315809	2242	0.754701
139	42	392	0.460683	447	0.960534	524	0.367961
140	162	7475	0.144310	7536	0.118303	7880	0.032575
141	100	2727	0.488414	2430	0.745240	2539	0.962977

APPENDIX L

Results of the Mann-Whitney-Wilcoxon test comparing contour slopes derived at 200m horizontal distance intervals with DEM20, DEM90 and DEM200 –derived slopes, for 109 river profiles in the X catchment (n = sample size)

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
1	1658	876348	3.75E-22	828854	4.43E-13	858646	1.79E-18
2	925	269380	1.07E-11	254537	6.68E-07	280131	4.68E-16
4	663	147447	3.50E-14	135807	1.80E-07	148044	1.37E-14
5	238	15286	0.316517	15038	0.442253	16261	0.055029
6	570	101179	4.75E-07	92194	0.005920	100228	0.000002
7	404	54451	8.03E-09	47433	0.005445	50199	0.000076
8	350	39584	2.83E-06	34043	0.078758	34407	0.051164
9	591	105225	1.90E-05	98226	0.009586	96062	0.038515
10	96	2884	0.042359	2900	0.036758	3171	0.002078
11	292	26092	0.001128	22774	0.337695	25455	0.004874
12	325	31176	0.005686	29092	0.124526	32710	0.000242
13	330	34191	0.000072	31742	0.010575	31751	0.010418
15	300	28262	0.000156	26506	0.008954	26232	0.015032
16	291	27254	0.000029	24981	0.009283	25485	0.003154
17	532	85832	0.000025	84051	0.000207	84939	0.000075
18	296	27980	0.000047	25486	0.017318	28678	0.000005
19	248	19805	0.000113	16755	0.244347	16687	0.269569
20	266	19668	0.127903	20654	0.021026	19920	0.084875
21	260	20234	0.007082	19082	0.081192	19517	0.035535
22	181	9031	0.260049	8403	0.812975	8867	0.371355
23	225	16678	0.000050	15173	0.011851	16118	0.000495
24	231	15447	0.043940	14987	0.118226	15830	0.016787
25	343	35092	0.002338	33110	0.049401	33416	0.033038
26	214	14110	0.004044	12750	0.169116	12504	0.269684
27	199	12895	0.000295	12214	0.005391	11565	0.047165
28	210	15682	0.000000	13262	0.013240	12582	0.088020
29	223	15836	0.000519	14238	0.069708	14388	0.048916
30	203	12591	0.007585	11753	0.094912	10346	0.993811
31	208	11747	0.312098	11112	0.779334	10199	0.441777
32	207	12050	0.136266	11048	0.742486	12249	0.085348
33	199	12485	0.001834	11233	0.114875	10770	0.313713
34	136	5089	0.349726	4936	0.546656	5157	0.278884
35	71	1348	0.690465	1246	0.856768	1470	0.272525
36	200	12168	0.009774	10755	0.390003	11826	0.030279
37	181	10286	0.003681	9404	0.097984	9479	0.078245
38	190	11022	0.010234	11262	0.003927	11990	0.000121

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
39	184	10315	0.012617	9174	0.359066	10471	0.006729
41	238	16767	0.016642	16289	0.051780	15320	0.301318
42	153	6263	0.498025	6463	0.297458	6772	0.108549
43	177	9685	0.008086	9067	0.081302	9554	0.014027
44	241	17166	0.017030	15622	0.336612	16436	0.086855
46	9	18	0.652344	26	0.734375	25	0.812542
47	168	9574	0.000088	7757	0.296986	7270	0.785916
49	154	7237	0.022073	6951	0.076197	6028	0.913812
50	94	2584	0.185636	2454	0.404632	2702	0.076965
52	147	7009	0.002400	5622	0.724152	6665	0.017795
53	163	6400	0.639709	6150	0.377588	6832	0.805633
54	161	7320	0.177467	7219	0.238749	6873	0.552429
57	66	1176	0.654750	1088	0.913521	1157	0.744582
58	151	6968	0.022367	7309	0.003528	7615	0.000490
59	145	5384	0.857455	5552	0.609205	5949	0.195384
60	137	5224	0.285603	5157	0.355557	4658	0.883843
61	122	4984	0.001645	4397	0.099357	4542	0.043544
62	113	3659	0.209551	3162	0.868030	3415	0.578360
63	124	4786	0.023177	4438	0.160705	4229	0.378038
64	119	3735	0.662652	3647	0.839238	4012	0.241669
66	119	4235	0.078047	3436	0.723326	3994	0.261418
67	117	3719	0.467721	4216	0.037715	4055	0.100996
68	119	3871	0.425526	3604	0.929212	4216	0.086943
69	97	2779	0.148025	2818	0.112550	2874	0.073718
70	111	3111	0.994131	3609	0.140856	3566	0.178271
71	104	3157	0.166646	3057	0.289701	2903	0.575891
72	111	3567	0.177322	2821	0.399250	3165	0.867969
74	95	2490	0.436784	2512	0.390178	2846	0.035809
75	92	2366	0.377794	2351	0.410190	2276	0.595059
76	102	2966	0.257767	2866	0.424970	3142	0.085580
77	94	2390	0.553825	2461	0.389914	2213	0.942882
78	96	2927	0.028734	2442	0.678314	2519	0.486335
82	98	2720	0.297493	2481	0.845474	2894	0.097234
83	96	2563	0.391480	2449	0.659687	2361	0.905461
84	95	2243	0.892230	2299	0.945252	2475	0.470319
85	92	2468	0.200845	2216	0.765792	2599	0.073574
86	92	2309	0.509243	2209	0.786679	2271	0.608614
87	79	1780	0.329570	1770	0.354393	1467	0.582459
88	90	2649	0.015594	2387	0.172555	2479	0.082874
90	79	1880	0.143282	1480	0.626780	1435	0.480074
93	82	1924	0.304754	1972	0.211961	1527	0.421171
94	87	2002	0.711132	1997	0.726960	2178	0.264747

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
95	77	1572	0.722259	1652	0.446283	1577	0.703341
96	86	1968	0.676179	1957	0.711147	2092	0.341286
98	63	1218	0.151497	1139	0.371627	977	0.834600
101	71	1641	0.037794	1411	0.447731	1584	0.080037
104	72	1331	0.926227	1305	0.961956	1272	0.815850
105	73	1434	0.648176	1542	0.293702	1649	0.101364
106	66	1235	0.409896	1240	0.391989	1294	0.229762
107	66	1175	0.659373	1191	0.587138	1243	0.381483
108	65	1085	0.937495	889	0.231738	865	0.176141
109	154	7188	0.027757	6760	0.153103	7331	0.013944
110	66	1122	0.918591	1031	0.636414	1210	0.506460
111	57	897	0.578098	881	0.667893	826	1
113	53	793	0.495452	793	0.495452	1056	0.002613
114	53	820	0.357209	655	0.595304	779	0.577033
115	52	753	0.562976	720	0.781191	667	0.844761
116	53	999	0.012234	777	0.589184	860	0.202379
117	50	676	0.713747	601	0.728202	639	0.992298
118	48	654	0.505119	637	0.621887	592	0.971363
119	50	668	0.772124	563	0.475015	685	0.650042
120	33	289	0.886333	348	0.234644	298	0.764353
121	41	402	0.719560	451	0.797639	419	0.886651
122	44	508	0.884016	546	0.559202	552	0.513366
125	37	375	0.731629	346	0.940594	348	0.964336
126	30	198	0.489846	218	0.776569	179	0.280087
129	93	2318	0.613016	2581	0.130146	2759	0.028125
130	57	949	0.332346	913	0.494413	586	0.056536
131	41	440	0.908160	420	0.898007	401	0.709980
132	51	629	0.753513	674	0.921598	643	0.854969
139	22	116	0.750238	135	0.799034	163	0.247899
140	82	1881	0.407948	1959	0.234790	1886	0.394976
141	51	684	0.847619	609	0.616033	666	0.981304

APPENDIX M

Results of the Mann-Whitney-Wilcoxon test comparing contour slopes derived at 300m horizontal distance intervals with DEM20, DEM90 and DEM200 –derived slopes, for 109 river profiles in the X catchment (n = sample size)

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
1	1107	378352	1.58E-11	353102	0.000013	373204	3.94E-10
2	617	115369	6.05E-06	109167	0.001781	122558	7.87E-10
4	442	63525	5.85E-08	55974	0.008968	64669	4.94E-09
5	117	3456	0.991320	3507	0.881087	3755	0.409874
6	380	44114	0.000219	40915	0.027616	43239	0.001011
7	269	24002	0.000005	20318	0.090789	22503	0.000669
8	233	17367	0.000287	14356	0.481507	14728	0.286855
9	394	45772	0.002409	43566	0.039465	41474	0.256614
10	64	1188	0.323932	1303	0.079179	1395	0.017753
11	222	15535	0.000980	13664	0.179172	14096	0.072778
12	217	13416	0.086155	12420	0.521907	14407	0.005332
13	220	15009	0.002536	13644	0.115299	14077	0.042059
15	200	12189	0.009071	11359	0.110356	11509	0.075138
16	194	12478	0.000115	10804	0.085627	11040	0.043350
17	355	38146	0.000711	36891	0.006205	36347	0.014063
18	197	11864	0.008390	10990	0.122314	12753	0.000180
19	166	8936	0.001226	7214	0.648169	7536	0.329313
20	178	8513	0.426873	8879	0.184777	8545	0.400327
21	174	8688	0.106201	8395	0.239921	8694	0.104264
22	121	3801	0.776007	3542	0.701854	3945	0.511182
23	150	7374	0.001325	6267	0.257109	6863	0.024354
24	154	6558	0.287205	6854	0.109995	6729	0.169835
25	229	15219	0.040999	14009	0.402064	14684	0.130919
26	143	6246	0.026989	5569	0.396779	5421	0.582909
27	133	5549	0.014096	5337	0.047866	4950	0.267241
28	140	6979	0.000021	5564	0.191101	5373	0.362803
29	149	6900	0.012905	6056	0.375130	6493	0.086334
30	136	5531	0.058063	4867	0.650621	4476	0.693397
31	139	5138	0.566690	4978	0.813020	4228	0.180821
32	138	5249	0.335668	4781	0.976263	5368	0.224111
33	133	5253	0.073468	4953	0.264351	4926	0.291181
34	88	2164	0.392520	2077	0.621969	2223	0.271094
35	48	591	0.979734	610	0.827045	630	0.673089
36	133	4973	0.245608	4630	0.695967	5029	0.198147
37	121	4495	0.037559	4164	0.221155	4179	0.206854
38	127	4869	0.052895	4999	0.024539	5242	0.004607

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
39	123	4314	0.206487	4109	0.455758	4541	0.066324
41	159	7312	0.101778	7094	0.207166	6606	0.672890
42	102	2651	0.936145	2750	0.681369	2926	0.318223
43	118	4328	0.028233	3812	0.418906	4089	0.120616
44	161	7518	0.092416	6951	0.467976	6909	0.512540
46	109	3601	0.068299	3298	0.364419	3465	0.157988
47	89	2797	0.001160	2093	0.712710	1987	0.951065
49	103	3269	0.052049	3011	0.273999	2526	0.618185
50	63	1114	0.470132	1078	0.634214	1253	0.094156
52	98	2990	0.045632	2462	0.898490	2775	0.216194
53	106	2593	0.445604	2671	0.605218	2832	0.992455
54	105	2971	0.547840	2885	0.744368	2780	0.994899
57	44	505	0.911721	458	0.670125	512	0.847304
58	81	2009	0.101313	1952	0.170651	1972	0.143114
59	97	2358	0.948359	2379	0.994258	2544	0.547901
60	92	2488	0.174774	2293	0.550031	2006	0.605894
61	81	2075	0.051267	1955	0.166287	1964	0.153692
62	75	1448	0.905424	1336	0.640264	1552	0.504140
63	83	2014	0.219406	1875	0.550489	1938	0.377205
64	80	1604	0.940736	1546	0.724438	1765	0.488262
66	79	1751	0.404705	1664	0.683222	1795	0.294511
67	78	1638	0.629001	1900	0.073761	1849	0.125012
68	79	1791	0.303607	1586	0.978556	1856	0.178178
69	65	1199	0.410273	1207	0.381202	1331	0.091792
70	74	1381	0.974214	1527	0.453961	1569	0.329515
71	69	1404	0.241247	1240	0.848270	1328	0.473076
72	74	1571	0.324190	1281	0.567968	1347	0.829386
74	64	1132	0.540600	1104	0.671087	1222	0.224828
75	62	1023	0.747067	991	0.921809	928	0.736470
76	68	1298	0.446807	1204	0.852158	1354	0.270062
77	63	1025	0.910062	1059	0.729547	926	0.576870
78	64	1246	0.169354	1103	0.675970	1061	0.890956
82	65	1192	0.436769	1118	0.768703	1308	0.124609
83	64	1105	0.666218	1055	0.922751	1009	0.838377
84	63	1045	0.802677	1055	0.750224	1154	0.319196
85	61	960	0.919901	952	0.965624	1134	0.176900
86	62	1068	0.523467	954	0.877418	972	0.977626
87	53	749	0.770178	773	0.613834	675	0.723255
88	61	1158	0.127816	1109	0.241682	1117	0.219350
90	53	797	0.473328	615	0.376008	647	0.547182
93	55	749	0.863626	787	0.890046	592	0.136964
94	55	889	0.320775	840	0.560358	847	0.521546

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
95	51	692	0.789355	691	0.796583	718	0.609453
96	57	823	0.980984	887	0.633567	898	0.572679
98	42	526	0.358538	538	0.285443	445	0.940831
101	48	710	0.212699	597	0.931172	750	0.097913
104	48	632	0.658294	618	0.764305	595	0.947340
105	48	596	0.939253	636	0.626124	753	0.091562
106	44	547	0.547827	610	0.183318	542	0.587358
107	44	527	0.715829	530	0.690081	540	0.606899
108	43	489	0.853042	438	0.679975	360	0.176101
109	121	4315	0.106518	4247	0.150390	4482	0.040754
110	44	499	0.967750	405	0.299441	525	0.733174
111	38	385	0.840951	385	0.840951	368	0.976861
113	35	332	0.789553	300	0.814578	466	0.012395
114	35	350	0.572013	261	0.385466	319	0.954866
115	35	308	0.915164	312	0.967753	265	0.417468
116	35	305	0.877899	311	0.954866	370	0.376589
117	33	280	1	235	0.426360	310	0.608817
118	32	265	0.992644	290	0.637883	249	0.789126
119	32	259	0.933871	230	0.536062	264	1
120	22	130	0.923966	139	0.702385	130	0.923966
121	27	187	0.971726	215	0.546018	203	0.749598
122	28	226	0.613638	254	0.254513	217	0.762139
125	23	136	0.964313	131	0.846232	144	0.869667
126	20	104	0.985435	92	0.647655	86	0.498009
129	62	1063	0.546540	1118	0.322876	1212	0.099430
130	38	388	0.805263	388	0.807465	236	0.051233
131	27	180	0.840783	179	0.822338	188	0.990573
132	33	320	0.490893	285	0.943790	265	0.791411
139	15	38	0.229309	61	0.977966	66	0.761536
140	55	920	0.210354	820	0.678332	812	0.728052
141	34	312	0.810830	260	0.531753	293	0.946191

APPENDIX N

Results of the Mann-Whitney-Wilcoxon test comparing contour slopes derived at 400m horizontal distance intervals with DEM20, DEM90 and DEM200 –derived slopes, for 109 river profiles in the X catchment (n = sample size)

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
1	831	206656	0.000001	195595	0.001015	204332	0.000005
2	463	65296	0.000058	59057	0.063350	67927	0.000001
4	332	35349	0.000011	31676	0.021096	35308	0.000012
5	88	1909	0.840071	2019	0.801248	2045	0.718910
6	285	23583	0.021363	22082	0.221090	23587	0.021202
7	202	13290	0.000260	11234	0.237801	11773	0.067480
8	175	9254	0.020630	8203	0.454033	8211	0.446876
9	296	25193	0.029177	23557	0.284159	22165	0.899303
10	48	699	0.257065	741	0.118442	813	0.021301
11	167	8470	0.020026	7457	0.479501	8068	0.092281
12	163	7367	0.257406	7078	0.513320	8093	0.019517
13	165	7989	0.063389	7401	0.368250	7767	0.134847
15	150	6813	0.030952	6254	0.267492	6543	0.098719
16	146	6745	0.007059	6079	0.163644	6144	0.128534
17	266	21161	0.006704	20529	0.027246	20018	0.071686
18	148	6380	0.097151	6319	0.123075	6854	0.010284
19	124	4815	0.019139	4047	0.668895	4241	0.362064
20	133	4640	0.679439	4693	0.594549	4897	0.321978
21	130	4882	0.147062	4664	0.345467	4601	0.425436
22	91	1984	0.667608	2036	0.823052	2209	0.647571
23	113	4190	0.005499	3470	0.475632	3914	0.047106
24	116	3815	0.245565	3779	0.288229	3681	0.428340
25	172	8434	0.128361	7712	0.676932	8037	0.360937
26	107	3242	0.273264	2919	0.926947	3007	0.714968
27	100	2878	0.225464	2913	0.182745	2828	0.298288
28	105	3830	0.000817	3268	0.121033	2998	0.491884
29	112	3773	0.077303	3426	0.447752	3467	0.379837
30	102	2956	0.272090	2946	0.286911	2513	0.706014
31	104	2919	0.541018	2664	0.831788	2296	0.159793
32	104	2914	0.551805	2649	0.794057	2880	0.627818
33	100	3087	0.053530	2815	0.319543	2606	0.781944
34	66	1145	0.803256	1176	0.654755	1183	0.622802
35	36	322	0.870570	316	0.797889	386	0.414034
36	100	2746	0.448360	2539	0.962978	2769	0.402462
37	91	2464	0.142538	2268	0.489783	2319	0.372121
38	95	2622	0.204941	2757	0.076944	2828	0.042128

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
39	92	2430	0.257969	2280	0.584315	2556	0.104844
41	119	3927	0.344469	3849	0.460193	3689	0.753339
42	77	1494	0.971647	1485	0.935252	1745	0.217268
43	89	2390	0.113343	2101	0.688458	2315	0.201782
44	121	4281	0.126985	3858	0.665768	3975	0.462586
46	82	1946	0.259320	1896	0.369799	1839	0.526506
47	67	1491	0.028112	1196	0.724137	1152	0.937762
49	77	1775	0.165691	1712	0.286302	1463	0.847002
50	47	641	0.421705	592	0.773105	691	0.182402
52	74	1671	0.127312	1334	0.775243	1604	0.244566
53	80	1546	0.724440	1407	0.308100	1636	0.940737
54	79	1768	0.359496	1717	0.504718	1547	0.873803
57	33	272	0.887851	249	0.584276	289	0.886333
58	61	1115	0.224789	1069	0.376975	1110	0.238806
59	73	1269	0.656101	1384	0.856038	1358	0.969302
60	69	1256	0.774120	1277	0.679938	1112	0.570035
61	61	1156	0.131457	1105	0.253429	1091	0.297642
62	57	842	0.905134	771	0.662121	798	0.823951
63	62	1150	0.225162	1069	0.518915	1016	0.784521
64	60	915	1	948	0.810908	950	0.799512
66	60	977	0.650737	877	0.782502	987	0.598642
67	59	880	0.972904	1080	0.142082	1056	0.198119
68	59	904	0.888946	746	0.295841	1072	0.159221
69	49	696	0.409014	719	0.291691	664	0.611934
70	56	796	0.990238	821	0.854379	915	0.341960
71	52	749	0.587914	733	0.691994	719	0.788196
72	56	881	0.500971	652	0.235285	723	0.543385
74	48	611	0.819134	635	0.636348	755	0.087685
75	46	534	0.948241	547	0.948241	512	0.761870
76	51	700	0.732245	678	0.891888	734	0.508722
77	47	535	0.765088	573	0.929007	574	0.920680
78	48	619	0.756560	599	0.915032	626	0.703049
82	49	649	0.722613	601	0.913658	715	0.310282
83	48	610	0.827045	560	0.779866	526	0.531541
84	48	569	0.850878	573	0.882860	679	0.356534
85	46	547	0.948241	544	0.974107	616	0.412550
86	46	546	0.956858	538	0.982736	539	0.991283
87	40	425	0.847156	416	0.941724	393	0.826382
88	46	668	0.166797	622	0.379652	631	0.325464
90	40	406	0.962896	353	0.451734	301	0.146089
93	41	400	0.700445	481	0.520996	367	0.418289
94	41	474	0.581124	483	0.504412	485	0.488104

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
95	39	399	0.905576	416	0.724881	411	0.777263
96	43	456	0.843677	488	0.862427	511	0.653854
98	32	290	0.637883	276	0.832040	257	0.904596
101	36	391	0.370733	360	0.680739	438	0.100636
104	36	377	0.498910	324	0.895068	295	0.560127
105	36	345	0.858365	367	0.602815	426	0.147700
106	33	302	0.711099	323	0.458007	296	0.788682
107	33	313	0.572177	309	0.621252	309	0.621252
108	33	255	0.659182	257	0.684959	222	0.304337
109	91	2416	0.201805	2305	0.402537	2535	0.080560
110	33	270	0.860067	224	0.321474	276	0.943790
111	29	204	0.781862	230	0.798276	200	0.717209
113	27	182	0.877918	178	0.803988	279	0.029905
114	27	200	0.803988	156	0.441044	183	0.896588
115	26	201	0.525294	165	0.802801	164	0.779946
116	27	167	0.610933	183	0.896588	222	0.441044
117	25	157	0.894860	159	0.936803	172	0.811930
118	24	160	0.789838	161	0.768296	131	0.597084
119	24	158	0.833373	120	0.406112	147	0.944107
120	17	73	0.889969	75	0.963226	70	0.781906
121	21	96	0.516761	115	1	106	0.759288
122	21	124	0.785365	142	0.373725	122	0.838194
125	18	87	0.966118	80	0.831726	87	0.966118
126	15	60	1	63	0.890381	52	0.678772
129	47	566	0.987456	646	0.391877	710	0.123606
130	29	200	0.713160	208	0.848011	122	0.038632
131	21	97	0.539189	112	0.918694	104	0.707934
132	25	164	0.978915	167	0.915803	137	0.507704
139	11	18	0.206055	29	0.764648	42	0.464844
140	41	462	0.690956	482	0.512670	454	0.768080
141	26	183	0.861256	160	0.707846	183	0.861256

APPENDIX O

Results of the Mann-Whitney-Wilcoxon test comparing contour slopes derived at 500m horizontal distance intervals with DEM20, DEM90 and DEM200 –derived slopes, for 109 river profiles in the X catchment (n = sample size)

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
1	665	130947	0.000045	121057	0.037056	131319	0.000032
2	370	40831	0.001558	37794	0.091325	42728	0.000044
4	266	22467	0.000176	19882	0.090491	22617	0.000109
5	70	1162	0.639657	1266	0.892927	1320	0.652257
6	228	15343	0.021666	13834	0.433761	14894	0.064912
7	162	8154	0.009448	7141	0.367393	7638	0.083184
8	140	5708	0.108084	5147	0.659984	5172	0.622762
9	237	15722	0.125215	14356	0.810022	14057	0.966783
10	39	415	0.735266	498	0.134728	488	0.173631
11	133	5292	0.060450	4866	0.357165	4973	0.245603
12	130	4450	0.655490	4372	0.791086	4952	0.106822
13	132	4878	0.267203	4570	0.681830	4819	0.329304
15	120	4134	0.187298	4111	0.208259	4126	0.194408
16	117	4324	0.017707	3905	0.217922	4019	0.123042
17	213	13567	0.015919	12553	0.198870	12132	0.413765
18	118	4004	0.185520	3700	0.611767	4571	0.004419
19	100	2959	0.136089	2552	0.927401	2580	0.851356
20	107	2913	0.941776	2965	0.814477	3097	0.518983
21	104	3154	0.169649	3134	0.190713	3011	0.363029
22	73	1222	0.481628	1229	0.505919	1432	0.656101
23	90	2624	0.020461	2207	0.522324	2521	0.057014
24	93	2399	0.414426	2430	0.349835	2335	0.568062
25	138	5103	0.514101	4805	0.984739	5127	0.481761
26	86	2054	0.430698	1915	0.849729	1895	0.917690
27	80	1795	0.402555	1818	0.343502	1767	0.482269
28	84	2389	0.007114	2021	0.293590	1826	0.856665
29	89	2461	0.060955	2172	0.489294	2142	0.569564
30	82	1763	0.777944	1887	0.392414	1516	0.392417
31	83	1742	0.998189	1749	0.980078	1488	0.247897
32	83	1856	0.609514	1723	0.929453	1778	0.875533
33	80	1826	0.324310	1829	0.317295	1657	0.861029
34	53	713	0.985874	730	0.901364	755	0.729901
35	29	212	0.915216	200	0.717209	253	0.454879
36	80	1704	0.688796	1594	0.902657	1713	0.657291
37	73	1616	0.145157	1491	0.441503	1455	0.567494
38	76	1767	0.116107	1737	0.156774	1905	0.022266

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
39	74	1575	0.313732	1528	0.450721	1661	0.141367
41	95	2549	0.318942	2416	0.614995	2160	0.657355
42	62	1012	0.806156	964	0.932951	1044	0.638539
43	71	1477	0.255383	1359	0.644618	1432	0.379114
44	97	2604	0.414042	2594	0.434910	2614	0.393781
46	66	1156	0.749420	1194	0.574013	1213	0.494272
47	54	1050	0.008209	751	0.945084	651	0.433316
49	62	1085	0.448931	1111	0.347482	872	0.465908
50	38	406	0.615592	368	0.977133	446	0.280235
52	59	1001	0.383178	860	0.853288	955	0.599871
53	64	940	0.505789	948	0.540600	1129	0.553949
54	63	1084	0.605239	1091	0.572207	949	0.688790
57	27	177	0.785742	159	0.484606	198	0.840783
58	49	718	0.296264	688	0.459018	637	0.812970
59	58	740	0.373265	804	0.692946	873	0.895285
60	55	835	0.588910	831	0.612223	722	0.690644
61	49	704	0.365354	721	0.285434	759	0.147543
62	45	520	0.982168	478	0.662754	521	0.973255
63	50	678	0.699400	665	0.794371	661	0.824294
64	48	493	0.332405	540	0.626124	603	0.881767
66	48	563	0.803367	617	0.772074	638	0.614710
67	47	574	0.920680	721	0.097986	635	0.459165
68	47	594	0.757096	538	0.789209	681	0.219851
69	39	448	0.426539	459	0.343026	462	0.322156
70	45	502	0.866861	569	0.568300	564	0.606891
71	42	488	0.655847	445	0.940831	448	0.970396
72	45	588	0.433120	432	0.340713	473	0.622642
74	38	354	0.818591	416	0.518291	477	0.124229
75	37	359	0.916904	370	0.788427	295	0.402604
76	41	468	0.635058	426	0.959111	482	0.512670
77	38	356	0.840951	337	0.635953	362	0.908714
78	39	445	0.451174	392	0.983491	385	0.950500
82	39	420	0.683851	379	0.884820	429	0.594945
83	39	418	0.704261	379	0.884820	373	0.819906
84	38	372	0.988565	386	0.829754	415	0.527660
85	37	374	0.742885	333	0.788427	405	0.428414
86	37	370	0.788427	345	0.928741	340	0.869759
87	32	254	0.860930	269	0.933871	223	0.454045
88	37	427	0.257850	416	0.338376	417	0.330826
90	32	276	0.832040	215	0.369401	261	0.963233
93	33	278	0.971878	291	0.860067	239	0.468833
94	33	309	0.621252	281	1.000000	315	0.548331

REACH NUM	n	DEM20		DEM90		DEM200	
		V	p	V	p	V	p
95	31	231	0.746430	263	0.779347	261	0.809166
96	35	289	0.679870	310	0.941991	330	0.814578
98	25	175	0.750993	184	0.578206	138	0.524913
101	29	276	0.213245	242	0.608884	247	0.536151
104	29	210	0.881510	232	0.765542	198	0.685574
105	29	179	0.416920	233	0.749322	274	0.229707
106	27	183	0.896588	225	0.399743	183	0.896588
107	27	187	0.971726	230	0.336140	177	0.785742
108	26	178	0.960180	159	0.689320	140	0.380194
109	73	1591	0.187030	1431	0.660079	1578	0.212047
110	27	170	0.661680	158	0.469840	207	0.678951
111	23	127	0.753985	142	0.916847	123	0.664999
113	21	127	0.707934	107	0.785365	161	0.119342
114	21	128	0.682714	98	0.562075	113	0.945745
115	21	117	0.972271	109	0.838194	108	0.811678
116	21	124	0.785365	100	0.609149	144	0.337660
117	20	100	0.869488	85	0.474905	107	0.956329
118	20	99	0.840822	101	0.898317	86	0.498009
119	20	120	0.595819	92	0.647655	102	0.927279
120	14	35	0.295776	49	0.855225	54	0.951538
121	17	75	0.963226	78	0.963226	69	0.746658
122	17	91	0.517090	87	0.644135	79	0.926514
125	14	43	0.583008	48	0.807739	51	0.951538
126	12	37	0.909668	38	0.969727	40	0.969727
129	38	363	0.920085	448	0.267489	464	0.177424
130	23	127	0.753985	126	0.731389	72	0.044876
131	17	62	0.517090	61	0.487381	64	0.579056
132	20	100	0.869488	90	0.595819	83	0.430433
139	9	14	0.359375	19	0.734375	27	0.652344
140	33	287	0.915770	318	0.508534	294	0.816316
141	21	118	0.945745	109	0.838194	129	0.657827