Cartography M.Sc.

Master thesis

Generalisation of heterogeneous topographic linear features to derive a German Alpine club map

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2021

TECHNISCHE UNIVERSITÄT DRESDEN

Generalisation of Heterogeneous topographic linear features to derive a German Alpine club map

Submitted for the academic degree of Master of Science (M.Sc.) conducted at the Department of Geosciences, Institute for Cartography, Technical University of Dresden.

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Date of submission:	10.09.2021

Statement of Authorship

Herewith I declare that I am the sole author of the submitted Master's thesis entitled:

"Generalisation of Heterogeneous topographic linear features to derive a German Alpine club map"

I have fully referenced the ideas and work of others, whether published or unpublished. Literal or analogous citations are clearly marked as such.

Dresden, 10.09.2021 Sifa Mawiyoo

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my co-supervisors, Prof. Dr.-Ing. Habil. Dirk Burghardt and Mathias Gröbe for sharing their bountiful knowledge, time and feedback on this research.

Secondly, I wish to thank the reviewer, Dr. Paulo Raposo, for the constructive input and questions during the proposal and review stages. I also wish to recognise Dr. Timofey Samsonov, for the tips regarding using the open-source tool for the automated conflation of a DEM with hydrographic lines.

Thirdly, I wish to appreciate the opportunity to be part of the Erasmus + program 2019-2021, learn from lecturers and different teaching experiences at the four partner universities, and my peers from the 9th intake.

Finally, I am grateful for my family, partner and friends that cheered, supported, and motivated me to the end.

The original digital elevation model used for this paper has been provided by AW3D of the Japan Aerospace Exploration Agency.

Abstract

Cartographic generalisation simplifies geographic representations for a specific audience and purpose. This paper examines the generalisation requirements specific to linear dataset when making an Alpine club map at a scale of 1:33,000. The paper highlights the challenges presented from heterogenous datasets such as global 30m resolution elevation models as well as crowdsourced datasets from OpenStreetMap. The generalisation requirement includes selection / omission of features, cartographic conflicts from overlapping features and miss-alignments between contour and digitised river features.

In addressing these challenges multiple toolboxes are tested using ArcGIS Pro to model semi-automated solutions. The first tool box uses generalisation tools for detecting graphical conflict and resolution for roads and other linear features. The second toolbox adopts an open-source python package for digital elevation model conflation and contour generation to standardise elevation and digitized river network data and improve the overall quality and visual representation of spatial data in a final production map.

Keywords: linear feature generalisation, displacement, network generalisation , DEM conflation

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Acronyms

1. SRTM – Shuttle Radar Topography Mission (NASA)
2. ASTER – Advanced Spaceborne Thermal Emission and Reflection Radiometer (NASA & Japan)
3. ALOS – Advanced Land Observing Satellite By JAXA
4. OSM – Open Street Map
5. DEM – Digital Elevation Model
6. GAEL – Generalisation based on Agents and Elasticity

1. INTRODUCTION

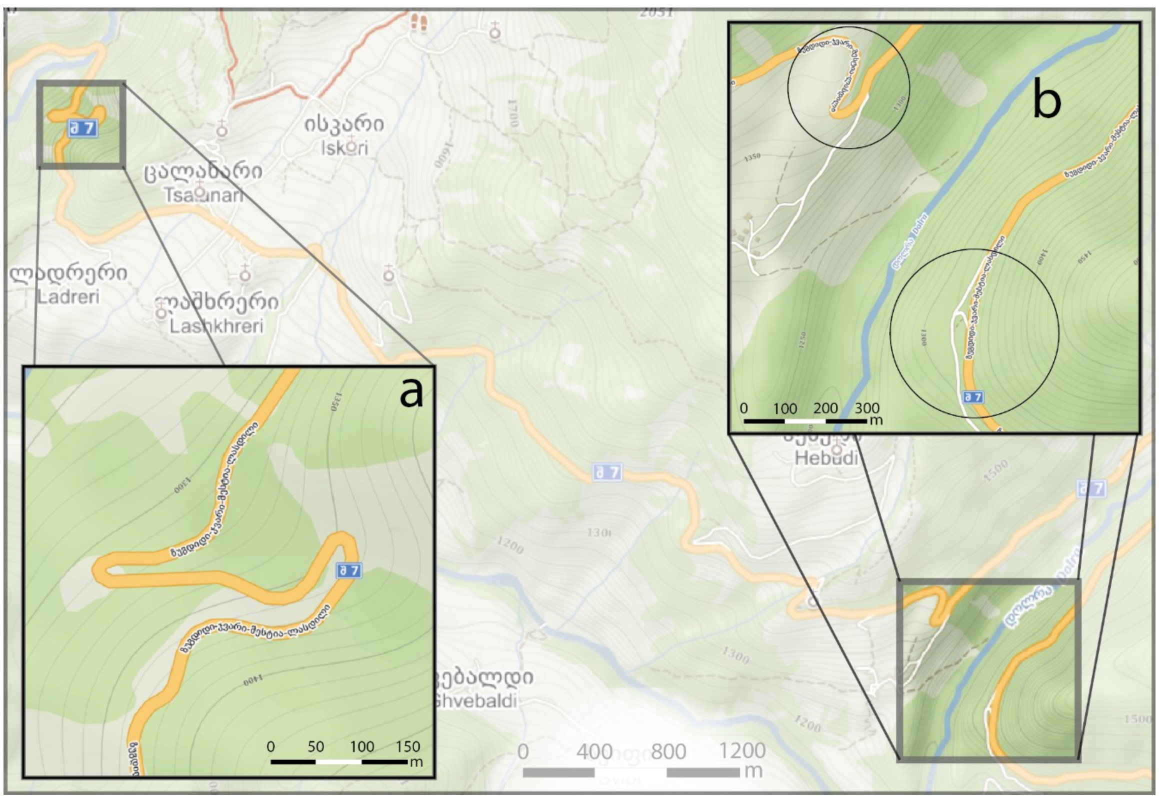
Alpine club maps are specially designed maps for outdoor enthusiasts who climb, hike and ski through and across the mountains and valleys of the alps in Germany and Austria. Over time additional mountain areas around the world are added to the catalogue. The study area for this project is located to the southern reaches of the Caucasus mountains around Mt Ushba in the Republic of Georgia. As part of an ongoing project mapping campaign, this thesis seeks to address generalisation challenges specific to Heterogeneous linear features required to make an alpine map. A generalisation process aims to simplify representation of geographic data in the map production process (Ruas, 2008). Cartographers often guide this process by influencing features to remove, enlarge, aggregate, displace etc. while aiming for "the optimal representation of geographic phenomenon at a range of different scales" (Mackaness & Chaudhry, 2008). Over the years numerous generalisation tools, operators and procedures have been designed to in part simplify and automate this process using mathematical models and standardising the outputs for repeatable and optimal results. This study therefore sees to co-opt a number generalisation approaches and parameters to support this campaign and support the generation of data covering linear features that are optimally adjusted for use in a 1:33,000 scale map.

1.1. Research Problem and Background.

The challenge for this mapping campaign is the limited availability of publicly available high quality and high-resolution datasets. In sourcing substitutes the campaign is faced with Heterogeneous datasets from different temporal periods, varying resolution, and different sources. The primary data source for linear features used in this project is OpenStreetMap (OSM). The crowdsourced features added this service are collected at levels 16 to 20. Zoom levels transfer to scales ranging between 1:8,000 to 1:500. This standard ensures new data is added at a large scale by default. The need for a suitable generalisation approach comes in to play immediately when considering the target scale of the map. Using these data sources created in a large-scale representational format for a small-scale map will result in a variety of visual errors. According to McMaster & Shea (1992), generalisation techniques counteract the undesirable consequences of scale reduction by reducing complexity, maintaining spatial and attribute accuracy, aesthetic quality, logical hierarchy, and consistent application of generalisation rules.

To illustrate, Figure 1 shows two examples of sub-optimal road representations at approximate a 1:36,000 scale. Example (a) shows roads with hairpin turns becoming indistinguishable at small scales. This does not reflect the path on the ground due to visible overlaps in the layer symbology. Example (B), the second case shows roads that are in proximity and parallel to other road segments also overlapping among these two different features.

Figure 1: Example of Road network errors visible on approx. 1:36000 scale map vs inset maps (a, b) magnified to approx. a 1: 2200 and 1:4500 scale maps respectively.

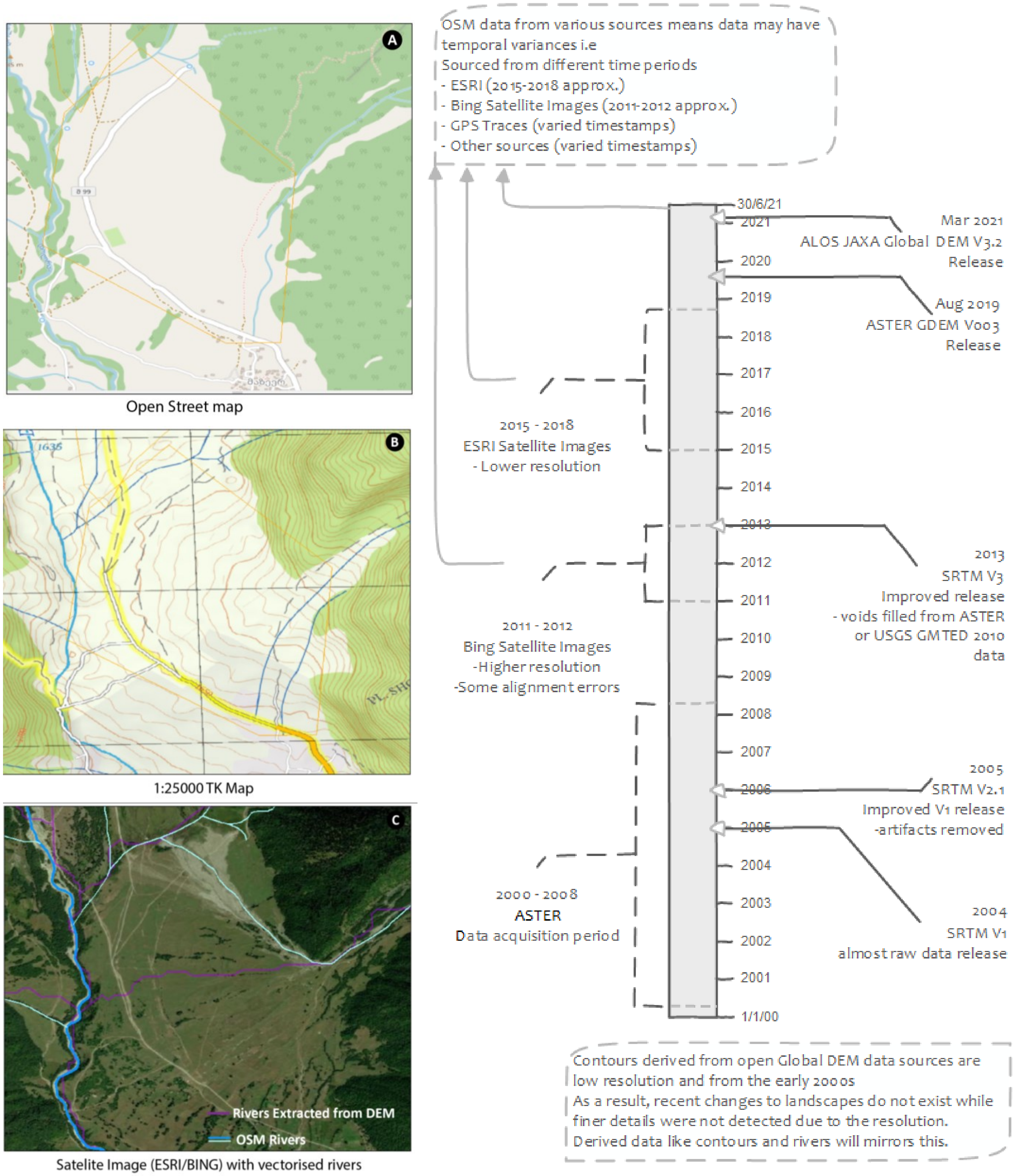


Source: *Mapy.Cz*, 2020

This occurrence is also known as coalescence when one feature overlaps with other features or self-coalescence where one feature coincides with itself (additional coalescence examples between road and rivers features is available in Appendix 1). To add to this the model solution required should also cater to linear features stored as both lines and as polygons such as river banks in OSM. Therefore, it is important to understand why, when and how to generalise in building an optimal generalisation model (Regnauld & McMaster, 2007).

The second challenge for the mapping campaign is handling generalisation in a dynamic situation where data is derived from various sources and finding ways to bring conformity across different datasets. To illustrate variety of Heterogeneous datasets available, a comparison of river data sources and contour and surface representations can be made in Figure 2. Part (A) shows vector data in OSM digitised by the crowd. Part (B) shows an official Topographic map at a scale of 1:25000. Part (C) shows the satellite image from Bing/ESRI, overlayed with a modelled extraction of rivers (purple) and proposed digitised rivers from Open Street map. In these images resolution and temporal differences reveal themselves in the variation of paths taken by the rivers course as the different perspectives and standards of acquisition influence the outputs. For example, the modelled rivers from the 30m SRTM DEM do not align with the current representation of digitised vectors on the map or erosion patterns visible in the satellite image and neither to the contours. Suggesting a lag in time or differences in the capture resolution. Elevation data used here is sourced from publicly available 30m resolution Digital Elevation Models (DEM) datasets like SRTM, ASTER or ALOS. Majority of these global DEMS are from the mid to late 2000’s. On the other hand the satellite data is more recent.

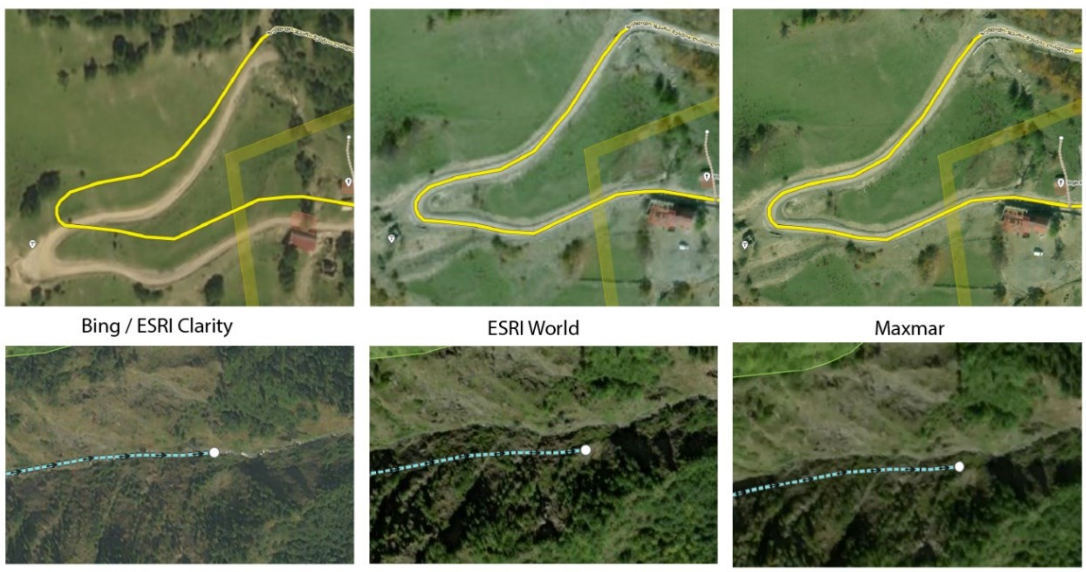
Figure 2: Heterogeneous Data Sources: Temporal and Resolution challenges for river courses and contours.



Source: OpenStreetMap Contributors, 2021

The experience of “the crowd” in digitising vector data and prior knowledge of troublesome aspects of available data sources means that some data will be digitised based on visibility instead of spatial accuracy in georeferencing. For example in Figure 3 the road and river positions is more accurate when digitised from ESRI world / Maxmar data sources as compared to vector data digitised from Bing / ESRI Clarity. The later pair are older and of a higher resolution while the former which are newer, of a lower resolution and better georeferenced.

Figure 3: Heterogeneous Data Sources: satellite imagery ground accuracy & variation impact on digitised vector data.



Source: OpenStreetMap Contributors, 2021

Even though not all challenges around the heterogeneous datasets will be solved here. This paper aims to achieve an improved level of agreement between contour lines and digitised river / waterways. To illustrate (Figure 4) the linear features available show that the contour lines do not correctly match the course of river.

Figure 4: Heterogeneous data sources: Example of Conflicting representation of contours not aligned to rivers due to data source mismatches.

Source: *Mapy.Cz*, 2020

Typically, in standard circumstances, waterways follow the lowest path within a valley (the thalweg) as there is a direct topological relationship in the landscape and the positioning of waterways. In this example however, there is a mismatch between the contours and the location of the waterways.

1.2. Research Objectives

This first objective of thesis is to explore generalisation methodologies that can solve coalescence conflicts across the available linear features. The core generalisation operators for the problems illustrated in Figure 1 is displacement. Two categories of displacement include a translation and or modification of features according to the set displacement parameters and direction (Li, 2006, p. 239) . The result of a displacement operation is that it will tend to pull features that are overlapping or touching (coalescing) apart.

An additional generalisation operator needed is a way to refine and optimise the content of the map. This will include a refinement process to remove or keep certain elements based on their importance and to support the hiking and outdoor thematic intention for the map. Refinement can increase or decrease the content load of the map and less content will provide needed space for other types of features that can be displayed on the map. To do this correctly the compromises made will maintain sufficiently clear navigational routes through-out the whole network while minimising repetitive, unneeded, and isolated of the network.

The second objective is to explore solutions to harmonise two heterogeneous datasets namely the contours and the river network. Contours are a derived dataset generated from height measurements of the ground in multiple locations. The rivers are also a derived dataset generated mostly from satellite imagery extractions. From the examples in the background both datasets are competing against each other claiming to be correct, however both are incorrect due to resolution or the underlying offsets in the satellite imagery during acquisition. A homogeneous situation where hydrological accuracy and terrain accuracy are in bonded together is valuable for the quality of future maps produced using similar datasets.

The third objective regards building modelling solutions that are fully or partially automated and capable of generating the improved generalised cartographic results. A model offers a repeatable and standardised workflow for users.

1.3. Research questions

To archive the research objectives the following research questions, need to be answered.

1. Which generalisation approach can be used to refine the network of linear features and optimally reduce the content load at the set scale for the target use case?
2. Which generalisation algorithms/approaches can be used to detect and resolve standard coalescence and self-coalescence conflicts?
3. What generalisation and spatial adjustment process can be used to harmonise topographical representations between contours and waterways from heterogeneous data sources?

1.4. Motivation

The motivation for this paper is to provide solutions that automate or partially automate the resolution of conflicts within heterogeneous linear datasets. This would improve the quality of outputs and additionally standardise broken links in spatial datasets that exist in the physical world that they represent.

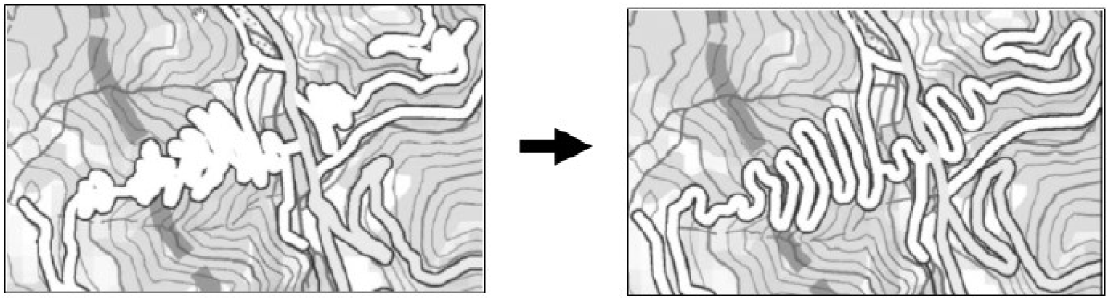
2. Literature Review

2.1.1. Road and Road Network Generalisation

A key part of generalising road networks is the selection of roads or omission operations that filter roads which can be allowed to participate in the generalisation process. Yan (2019, p. 99) highlights a number of groups of selections algorithms and an improved approach based on the cartographic information theory. The first group involves Semantic based algorithms which uses street type, rank order and relative importance of attributes for the selection. The second group of algorithms are graph based which considered the network as a connected graph and focuses on topological relationships and centrality as key to the selection process. The third group uses stroke-based algorithms that focus on strokes of the roads as important aspect for good continuation in dense urban centres. The fourth algorithm is more comprehensive, and it attempts to combine metric, statistical, topological, and thematic information at different scales such as macro mezzo and micro in the road network selection. The essential aspect of this is that the quantity of features involved are reduced, "without losing the connectivity between important places on the map"(Regnauld & McMaster, 2007). This has the effect of making room for other aspects of generalisation that will be requires such as simplification, typification, collapse, and displacement etc to take place with the remaining features.

According to Sester (2008, pp. 7–8), in comparison to model-based generalisation, full automation can be difficult to achieve particularly for graphic or cartographic based generalisation as complex situation sometimes depend on a cartographer solve particularly for some typification and displacement requirements. One ideal example of a displacement solution is presented by Gaffuri (2007, p. 2), in Figure 5, showing the resolution of coalescence conflicts using a displacement operator.

Figure 5: Result of Overlapping conflict solution solved with an Agent-based generalisation model



Source: Gaffuri, 2007

This Agent based generalisation model of Ruas works on the principle of identifying cartographic conflicts then applying a locally specific transformation for the features that are in continuous conflict automatically (Gaffuri, 2007). The standard model consists of three components; agents, (for example roads with their own design goals and objectives), cartographic constrains (the goals the agents are trying to achieve) and the levels for consideration (micro level concerns objects independently while meso level concerns groups of objects considered together). Continuous operations form smooth changes to discrete operations particularly for linear features. Therefore, when a discreate displacement operator affects part of a road, a continuous operation can be applied subsequently to diffuse the displacement and deform the road or relief while maintaining the overall shape and representation of the feature.

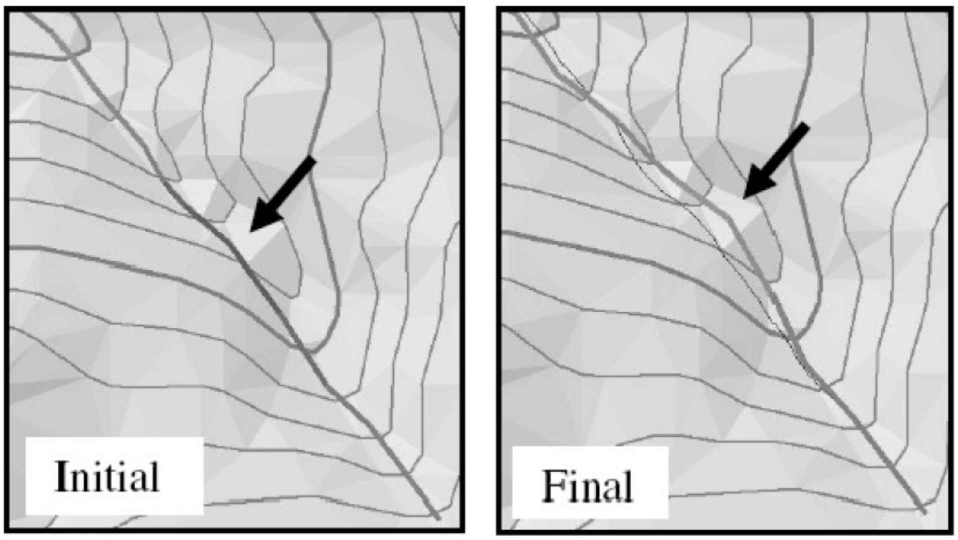
A developed and commercially available solution for generalisation is ESRI's user directed generalisation approach for roads and buildings in multiscale cartography (Punt & Watkins, 2010). It presents an optimised constraint-based method of modifying geographic features based on constraints that clarify the features displayed at changing scale levels. The optimisation approach uses a ranking system and defined hierarchy that sets the order in which features that conflict are adjusted. Features that have hard constraints and cannot be adjusted are reflexes that go back to their original state while other features take a simulated annealing approach to be processed. The development of this generalisation approach resulted in a number of the cartographic generalisation tools in their software. This includes the thin roads network tool, merge divided roads tool, propagate displacement, and resolve road conflicts tools (ESRI, 2021a; Punt & Watkins, 2010). Research into similar solutions have further supported the idea that using a combination of algorithms for different road features and characteristics which in turn outperformed using one generalisation solution (Park & Yu, 2011). For road generalisation and requirements, a hybrid approach to the shape characteristics of the segments is considered to produces less positional errors than the individual application of a single simplification algorithms. Some automated approaches attempts to understand the local characteristics of the data and adjust the algorithm in use to the local situation on the fly as seen with the thin road networks tool or alternatively models themselves can be adjusted to combine the best of two or more possible improvements to a generalisation model.

2.1.2. Contour and waterway Standardisation.

Contour line adjustment and standardisation with river can be addressed from different starting points. One is by detecting and correcting inconsistencies between the two linear features using spatial constraint knowledge (Ai et al., 2014). This technical approach identified the common situations for errors in contour representation of a landscape. The first. Is when a contour drops into a double line river, or a river partly climbs up a slope or a river deviate from its talweg. A river deviating from its talweg is the most common type of error including got the study area region. However other causes for this kind of errors can include simplification and map generalisation. In this approach constraints state that rivers and contours should intersect at valleys and their flow should be in the direction height decreases without deviating from the talweg (Ai et al., 2014). Using these characteristics, the valley bottoms are used as reference points to move offset intersections between contours and rivers to their correct positions in the valleys.

In the expansion of the traditional agent-based generalisation model Gaffuri (2007), developed the Generalisation based on Agents and Elasticity Model (GAEL) for continuous transformations by adding a new level termed the submicro level. This considers parts of objects based on internal constraints (shape preservation), external constrains (deformation requirements) and the balance or resulting deformation (displacement of some parts of the object) in an agent-based deformation model. Gaffuri's (2007, pp. 18–19) GAEL model used a hydrographic network to deform the relief and improve the outflow relationship illustrated here in below.

Figure 6: Example result from applying the GAEL Model to deform the relief using the hydrographic network.



Source: Gaffuri, 2007

A similar point for correcting the relationship between contours and rivers is to address errors in the source data of contours. Contours are can often be derived from DEMs and for this project the DEM data available is also not optimally aligned river dataset. Samsonov's (2020) approach to this is through his python toolbox on the Automated conflation of DEMs with reference hydrographic lines rather than editing the contours it also directly modifies the DEM. This approach also enhances certain geomorphological features of the DEM including ridges and valleys. This means that a new improved DEM can be reused to generate new contours that match the rivers of for other cartographic and analytical purposes. This approach sets the existing river as the reference position of the valleys in the DEM dataset and extracts counterpart streams in the DEM that match the reference rivers. Using common spatial adjustment technique, it stretches and pulls on parts of the surface to combines its counterpart streams to their correct position.

The main caveat with this approach is that it was made using reference data at 1:10,000,000 scales and its use and effectiveness at a scale of 1:33,000 remains unknown.

If effective this approach also provides an opportunity to run traditional generalisation approaches for contours which do include line simplification by filtering the DEM or directly smoothing and simplifying the contour line to the destination scale (Guilbert et al., 2014). In the former circumstance Grid based filtering and simplification methods tend to be more enduring for large scale maps as the contours tend to be topologically correct.

3. Methodology

The methodologies co-opted to solve the highlighted problems of coalescence and misaligned contours is contained in two models / approaches. The first approach (section 3.1) discusses a model solution for road generalisation that focuses on refinement and displacement of linear features. The second approach (section 3.2) discuses a model for DEM conflation and contour generation as an approach to adjusting the DEM to align with the course of a reference hydrological river dataset. Subsequently this harmonised dataset is the used to produce an optimised contour dataset that shows improved alignment to rivers and streams in the area.

3.1. Linear Feature Generalisation

The cartography toolbox within the ESRI's ArcGIS Pro software has available tools mentioned in the literature review such as resolve road conflicts, thin road networks, graphical conflict detection and a propagate displacement tool that are useful in solving overlapping and displacement challenges. Together they can be used for linear features like roads and rivers and adapted to the requirements for the task at different reference scales.

3.1.1. Data refinement – Thinning of line features in the Network

The data refinement process is an automated and parametrised approach to generalisation that select or omits features in the road network and creates space for more complex generalisation needs to take place. This process is carried out by the Thin Road Network tool which offers two key parameters for user input: A hierarchy and minimum length parameter. The hierarchy is used to define the importance of a feature and its significance in the network of features. Features with the lowest value hierarchy 1 are the most important and can range up to a hierarchy 5 level the least important. The process of thinning the road network also considers the connectivity of the road network. The more a feature is connected to other parts of the network, the more likely it is to be maintained in comparison to isolated road segments as one example. The second parameter is the minimum length distance. It is used to indicate which roads should be removed from the dataset based on a features' length. A general guideline for these parameters is provided bellow at various standard map scales.

Table 1: Guideline of Minimum length distances for different map scales and majority road network patterns

	Organic, non-gridded road patterns			Regular, gridded road patterns		
Final scale	Map units		Page units	Map units		Page units
1:25,000	250 m	825 ft.	1 cm	500 m	1,650 ft.	2 cm
1:50,000	500 m	1,650 ft.	1 cm	1,000 m	3,300 ft.	2 cm
1:100,000	1,000 m	3,300 ft.	1 cm	2,000 m	6,600 ft.	2 cm
1:250,000	2,500 m	8,250 ft.	1 cm	5,000 m	16,500 ft.	2 cm
1:500,000	5,000 m	16,500 ft.	1 cm	10,000 m	33,000 ft.	2 cm

Source: ESRI, 2021b

Based on the map unit the roads shorter than these distances will be suggested for removal. A generic example is showing bellow.

Figure 7: Example Image showing results from using the thin road network tool to eliminate insignificant road segments.

Source: Punt & Watkins, 2010

For this to work, accurate topology plays a key role in the outcome for the correct segments of the road to be removed. The tool also removes sections of the network that exist in parallel to other section of the network. A good example is for the elimination of sidewalks and paths that run parallel a main road that has a higher significance, lower hierarchy value and is critically important for connectivity to more parts of the road network.

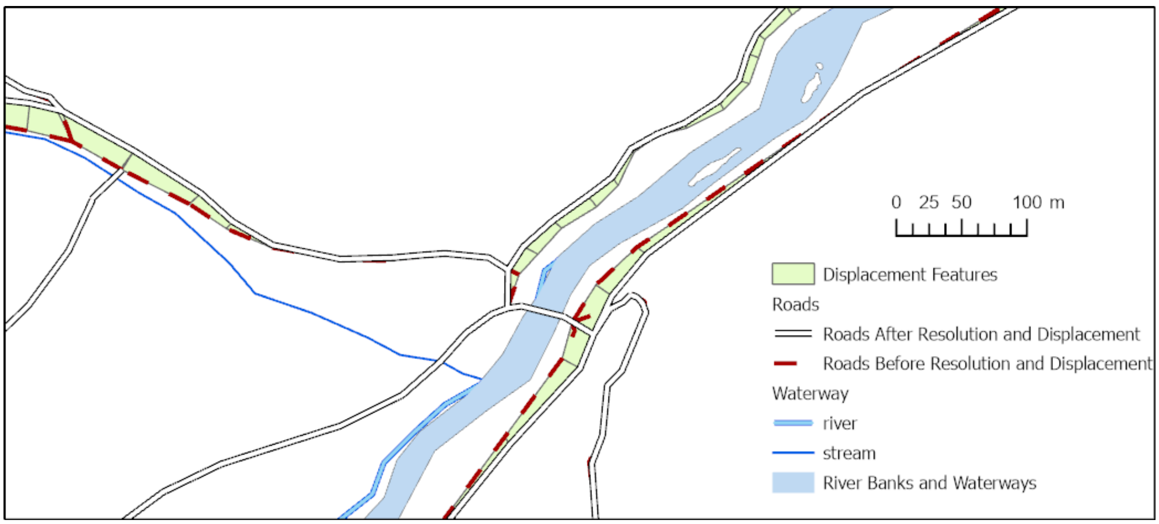
3.1.2. Graphical Conflict Detection and Resolution

For the purpose of this section Graphical conflict detection will be described in two forms. The first form is passive and does not include any kind of resolution. This passive form uses the ‘Detect Graphical Conflict tool’ to assess at a graphical level the areas that the symbology of two or more features conflict with each other (ESRI, 2021b). Conflict in these cases is defined as areas that the symbology would overlap with one element on top of another element. The output of this passive form is a polygon to indicate the area of over lapping features. Although it is possible to a configure the sensitivity of conflict detection by adjusting the Conflict Distance parameter. The default value is “0” which is sensitive to symbology that overlaps each other. Increasing this value however can create an additional buffer area of sensitivity. The second parameter is a Line Connection allowance distance that is used to reduce false positive detections in graphical conflicts where line ends meet specifically attuned to symbology applied to the end of a line and less so to intersecting lines with no line cap.

The second form of conflict detection is active and includes an approach to resolve graphical conflicts. Resolution is initiated by the ‘Resolve Road Conflicts’ tool and the resolutions specifications are implemented by the Propagate Displacement tool (Punt & Watkins, 2010). The resolution specification information is stored in a displacement vector containing the direction and distance required for the displacement. Displacement moves overlapping segments outwards and a way from one another. The order and direction of movement is dependent on a predetermined conflict hierarchy attribute assigned to each feature. This conflict hierarchy is set between the values of 1 (most important) to 5 (least important). With the conflict hierarchy set, a less important feature will be moved away from a more important feature i.e. Motorway adjacent to residential road, or river adjacent to road (unlike features). The displacement process will result in a gap between these features no less than 0.3mm and therefore visually appear as separate features. An additional value for the conflict hierarchy value is the option to set the value to zero. This means that the features with these values cannot be moved to accommodate other features of higher values. For features of the same conflict hierarchy value (like features) such as two parallel roads overlapping features are displaced apart from each other with no gap. In a second scenario two similar parallel features that do not overlap but are of the same hierarchy and type can be snapped together and shown with no gap in between them.

To support conflict resolution, displacement vectors indicate the distance and direction of adjustment needed at the reference scale for all segments of the line that are in conflict.

Figure 8: Example of Displacement features and effect of displacement on a line feature.



These vectors are implemented smoothly by the second part in the resolution process which is handled by the 'Propagate Displacement' tool. The function of this tool is implementing the displacement of the line segments in the predetermined manner and while also maintaining spatial relationships to other features. At a conceptual level this is like a rubber sheeting process that moves segments by the displacement distance and direction while attempting to maintain the lines original form.

3.2. Using DEM Conflation for River network matching and contour line generation

The approach for contour feature adjustment uses Conflation to apply a spatial adjustment technique for modification of a DEM from one data source and topographically match it to a hydrological dataset of rivers from a separate data source. In this way the adjusted DEM can be used to generate a new set of contours that suitably match the rivers dataset. When overlayed together, the rivers follow the talweg of the valley exactly and the contours from the conflated DEM are more closely aligned to this flow pattern when compared to contours from the source DEM.

3.2.1. Pre-Processing – Modified Stream Orders

The first stage is to prepare the reference hydrographic dataset of rivers for use as part of the conflation process. To do this a modified stream hierarchy based on the Hack ordering is assigned to each river feature. The modified version of the hierarchy pays special attention to sections of the river with braided streams.

> The longest stream passing through the braid keeps its order, while its tributaries are classified as if they do not outflow from the main stream. Direct tributaries of the main stream receive the same order incremented by one, and the process continues recursively for tributaries of tributaries until the whole braid is processed (Samsonov, 2020, p. 6).

A visual illustration of the modified Hack Order can be viewed in the Appendix 2.

Beyond the modified hack ordering, five additional descriptors are added to the stream data to better describe the topological structure of the dataset including braided streams, deltas, and channels in such a way as to support the identification of matching stream counterparts from the DEM data. The summary of these descriptors how they should be applied is directly captured in here.

Table 2: Summary of Pre-processing input requirements for Hydrological Reference.

Field Name	Definition	Application
ID	Unique identifier	
CONFL	ID of stream that current stream outflows to	Outlet is the end node of the stream with CONFL = -1 Confluence is the End node of stream with CONFL ≠ -1
BIFUR	ID of inflowing stream to the current stream	Source is the start node of stream with BIFUR = -1 Bifurcation is the start node of stream with BIFUR ≠ -1
ITER	Number of iterations during which a counterpart of the current stream should be extracted	If CONFL = -1 and BIFUR =-1 then ITER =1 Then corresponding streams are excluded from the list and iterations begin starting with i=2 and continues with i = i + 1
ORDER	Modified Stream Order	
TYPE	Stream type with respect to bifurcation process	If the BIFUR = -1 the type is a 'main' If the BIFUR ≠ - 1 the type is a 'distributary'

Source: Samsonov, 2020, p. 8

3.2.2. Processing - Rubber Sheeting Vector data, rubber sheet links and identity links.

Following preparation of the reference data, the next stage is divided in to three parts:

The first part is to extract the counterpart streams from the DEM and identify which of the counterpart streams best fit the reference river system. The sensitivity of this extraction depends on the parameters used in the Extract Counterpart tool which includes the minimum flow accumulation, off stream penalty, catchment radius, maximum deviation and the deviation distance metric used in the calculation. The deviation distance metric is used as both a selection constraint for the best fitting candidate constraint and a method to assess the quality of the match as being either strong, regular, or weak. This allows for an opportunity to adjust the parameters early on and loosen or righten the constraints enforced by the solution.

Table 3: Summary of Recommendations for Counterpart Extractions.

Parameter	Definition	Application
Catch Radius *(r)*	Limits the maximum spatial deviation of a counterpart from its reference line	Minimum value = DEM Pixel size (*R*) Larger *r* values guarantee a counterpart will be extracted but finding flow line can be challenging if *r* value is close to *R* **Recommendation** catch radius is pixel size multiplied by positive integer value (*k*).
Minimum flow accumulation *(a)*	Defines lower limit of possible magnitudes of counterpart streams	Higher *(a)* value = more significant paths are identified as counterpart streams. too large an (a) value risks now matching counterpart being found. **Recommendation** the minimum flow accumulation *(a)* value is ≤ *(k)* integer value
Off stream Penalty (*w*)	Defines how strictly the least-cost counterpart will follow the drainage network defined by a	W value should be large enough to penalise algorithm from jumping from one stream to another while calculating the3 shorted path. **Recommendation** *(w)* is 10 times a positive integer value *(m)*
Maximum deviation	Maximum deviation distance of a counterpart stream from its possible reference line.	

Source: Samsonov, 2020, pp. 9–10

Once the counterpart streams are extracted the second part begins by using the generate conflation links tool to identify and create a set of conflation links that can be used in the spatial adjustment process. The conflation links define the magnitude and direction of adjustment needed or in other words if it needs to be stretched or moved to align it with the reference hydrographic lines. In addition to creating the conflation link dataset, the user must also create identity links. Identity links encompass the area within which the spatial adjustment can take place. They remain stationary and only features located inside the link area participate in the adjustment process.

Elevation data from the DEM is added to the rubber sheeting process by converting the raster to vector data. Working with vectors makes the rubber sheeting approach easy to calculate. The adjustment is made by the rubber sheeting tool which adjusts the position of points inside the conflation area by the magnitude and direction of the conflation links. The vectorised elevation dataset is then rasterised into an elevation surface for conflation.

The third part is the conflation process carried out by the Conflate DEM by link tool. The effect of this tool is to harmonises the elevation surface with the reference hydrological lines using the conflation links and identity links for the localised area around the stream. It should be noted that at the end of this stage the conflation process has had a direct impact of the x, y positioning of the DEM data at a local level around the streams. However, spatial adjustment must also be made to the raster along the z axis. This final adjustment of the vertical dimension is discussed in the post processing segment of this method.

3.2.3. Post processing - Exaggerating the Surface Landforms and Generating Contours

The post processing stage helps to ensure that the final surface is both cartographically and analytical correct. To do this the Carve DEM tool is used to ensure that the elevations in the DEM along the hydrographic reference line decrease monotonically and that there are no depressions or hills along the path of the river in the conflated DEM surface(Samsonov, 2020, p. 18). To magnify this effect visually the optional tool, Widen Landforms is used to broaden the surface along the reference lines and increase the visibility of the valleys on the surface. For analytical purposes stream burning can additionally be applied to the conflated DEM surface correct and improve surface drainage patterns. This paper focuses on the improvements that are possible in terms of the cartographic representation of contour lines. Therefore, instead the final steps include focus on contour generation. When applied with trimming and smoothing tools artifacts can be removed to produce a smooth generalised contours for the alpine map. A successful conflation process should then show improvements to the contours generated from this conflated DEM surface when compared to the contour lines possible from the source elevation model.

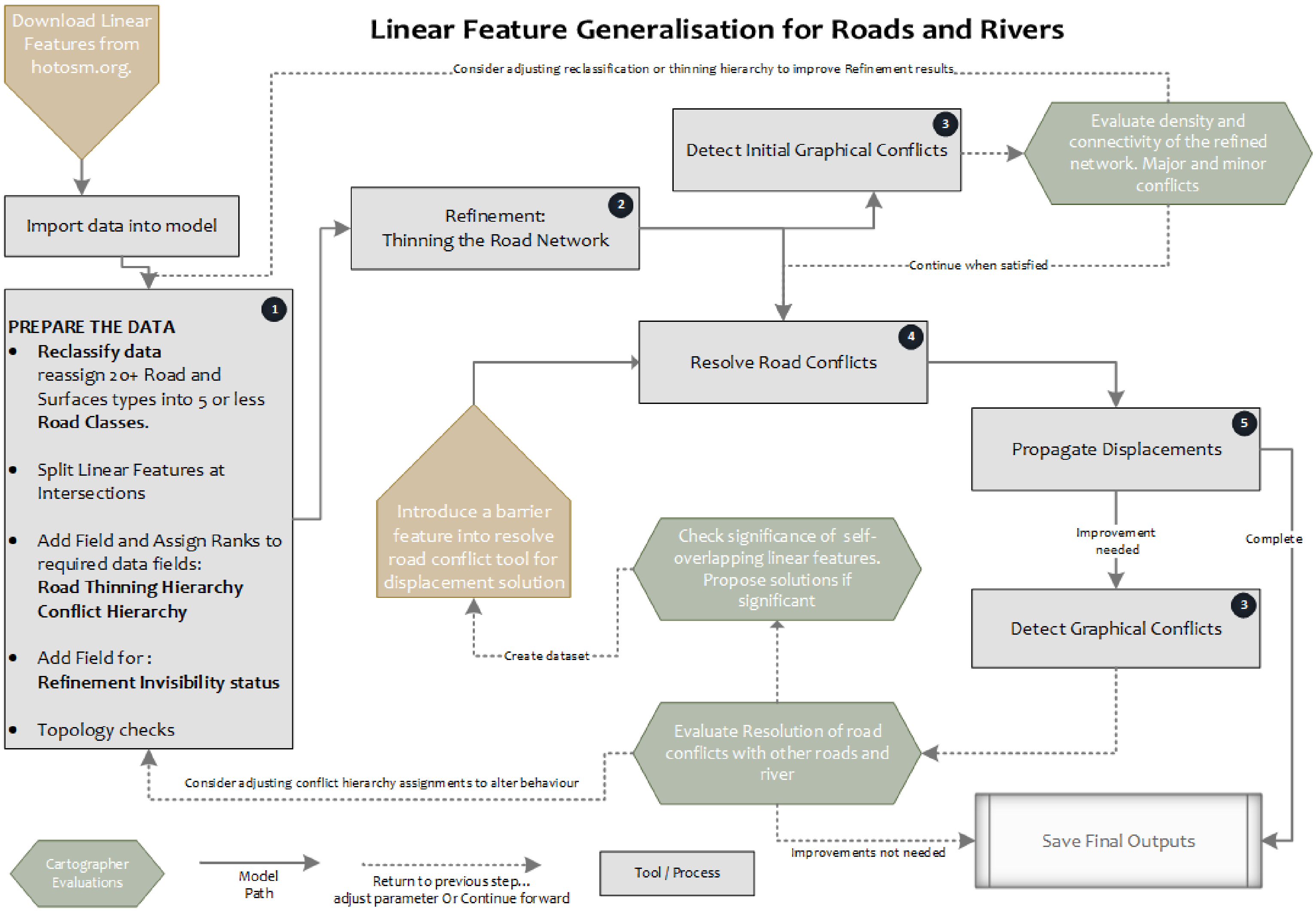
4. Implementation and results of Generalisation methods for linear features

The following sections elaborate on the specific parameters and tools used to build a semi-automatic model tools that can be used to implement the discussed methodologies for linear feature generalisation and DEM conflation as an approach for adjustment and matching of contours lines to a reference river drainage network.

4.1. Guide to linear feature generalisation

The implemented model for road generalisation can be summarised in to five key parts that will be covered in this section. An important aspect for this model is that it is semi-automated and requires the cartographer to review the outputs of the modelling process at key stages. This allows adjustments to be made to some parameters or include more data into the model. Once satisfied with the outputs the user can continue to the next stage of the process. Visually these processes are illustrated in Figure 9: Summary of Linear feature generalisation model for conflicting roads and rivers

Figure 9: Summary of Linear feature generalisation model for conflicting roads and rivers



4.1.1. Standardising Road Attributes and Parameters (Pre-processing)

This pre-processing component (Figure 9 Part 1) prepares the road data for use as part of the generalisation process. At an attribute level the user must reclassify the available road information into the classes needed for the output map product and suitable for classes for the model. For this Alpine map, four main classes namely: Main Roads, Roads, Tracks and Trails or Walkways were defined. The reclassification process as applied considered the surface of the roads as a key influencer in the classification beyond the standard road classes. Table 4 summarises the key value assignments for the different road classes.

Table 4: Summary of the reclassifications and road hierarchy

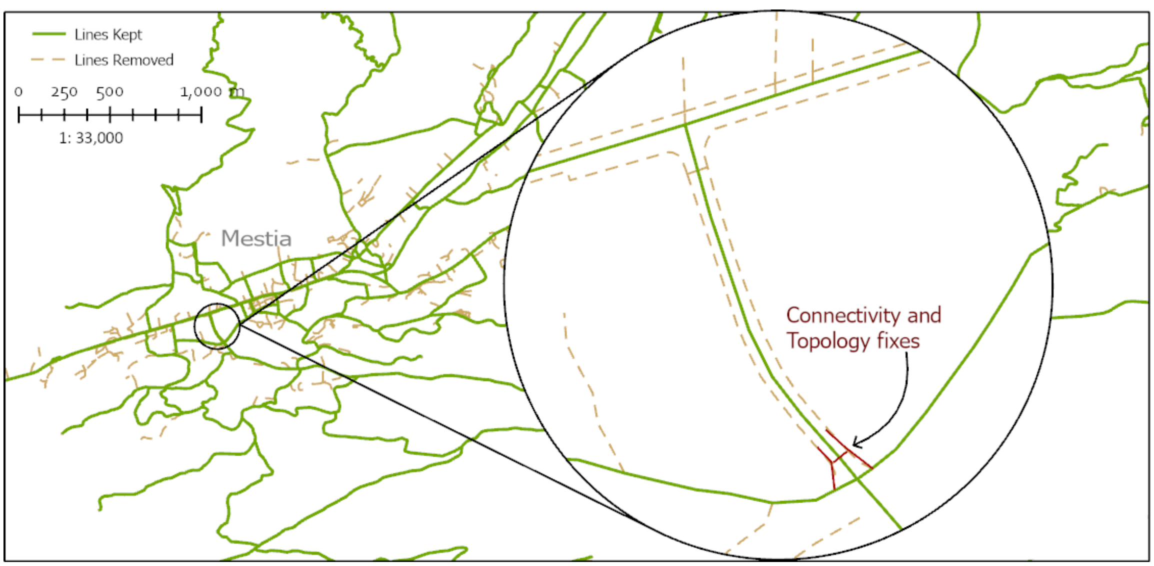
Reclassification structure	**Road Class**	**Thinning Hierarchy**	**Conflict Hierarchy**
Primary Roads *Secondary Roads*	Main Roads	1	1
Foot Paths *Pedestrian Steps* *Walkways*	Walkways	4	4
Tertiary Roads *Paved Residential Roads* *Primary Roads* *Paved Surfaces* *Asphalt Surfaces*	Roads	2	2
Service Roads *Undefined Road Classes* *Unclassified Surfaces* *unpaved, grass, pebble stone* *Other Residential roads* *Gravel, etc*	Tracks	3	3
Bridges	N / A	N / A	0
Rivers	N / A	N / A	0

In addition to the typification/reclassification of line features one additional pre-processing step is to ensure the correction of any topology errors that exist and could be detrimental to the results. As a network generalisation tool the overall network topology and connectivity play a role in the result. Implemented topology rules should include checks for pseudo nodes, dangling lines and overlapping lines. The model provided model includes a line split at intersection component to help enforce the last-mentioned topology check.

4.1.2. Road Network Refinement and Thinning

The road refinement and thinning task (Figure 9 Part 2) utilises the thinning hierarchy attributes defined in Table 4 above and minimum length parameter to determine which roads should be removed from the transport network at the desired scale of the output map. Based on the recommendation parameters in Table 1: Guideline of Minimum length distances for different map scales and majority road network patterns , three minimum distances were tested. Namely 300, 350 and 400 meters with the model configured with a default value of 400 meters for this parameter. Figure 10 below shows a sample area of the map and the roads that were maintained together with the roads that were removed from the network. The major point of caution for the user using this tool is to ensure that the dataset has reliable connectivity and accurate topology.

Figure 10: Sample results from thinning / refining road features: Additional data added to the roads features shown in red



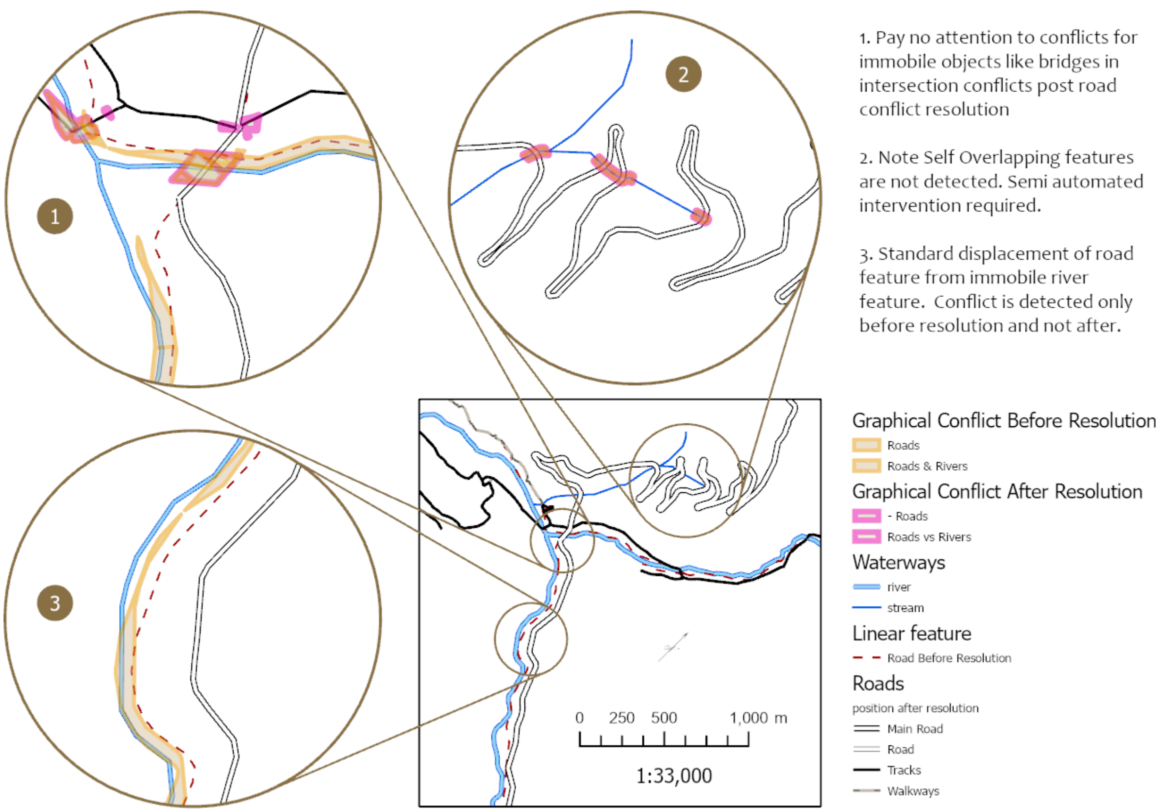
4.1.3. Graphical Conflict Detection

The graphical conflict detection tool (Figure 9 Part 3) was used at two different points in the modelling after thinning the road network and after the propagate displacement tool. This provided an opportunity see what conflicts were being detected before and after resolution of conflicts. The parameters used for this tool were:

Conflict distance = 0 points
Line Connection allowance = 50 m

At this setting symbols that physical overlap will result in polygons marking the overlap area. This is illustrated in the figure bellow.

Figure 11: Sample of graphical conflict detection results for road and river features.

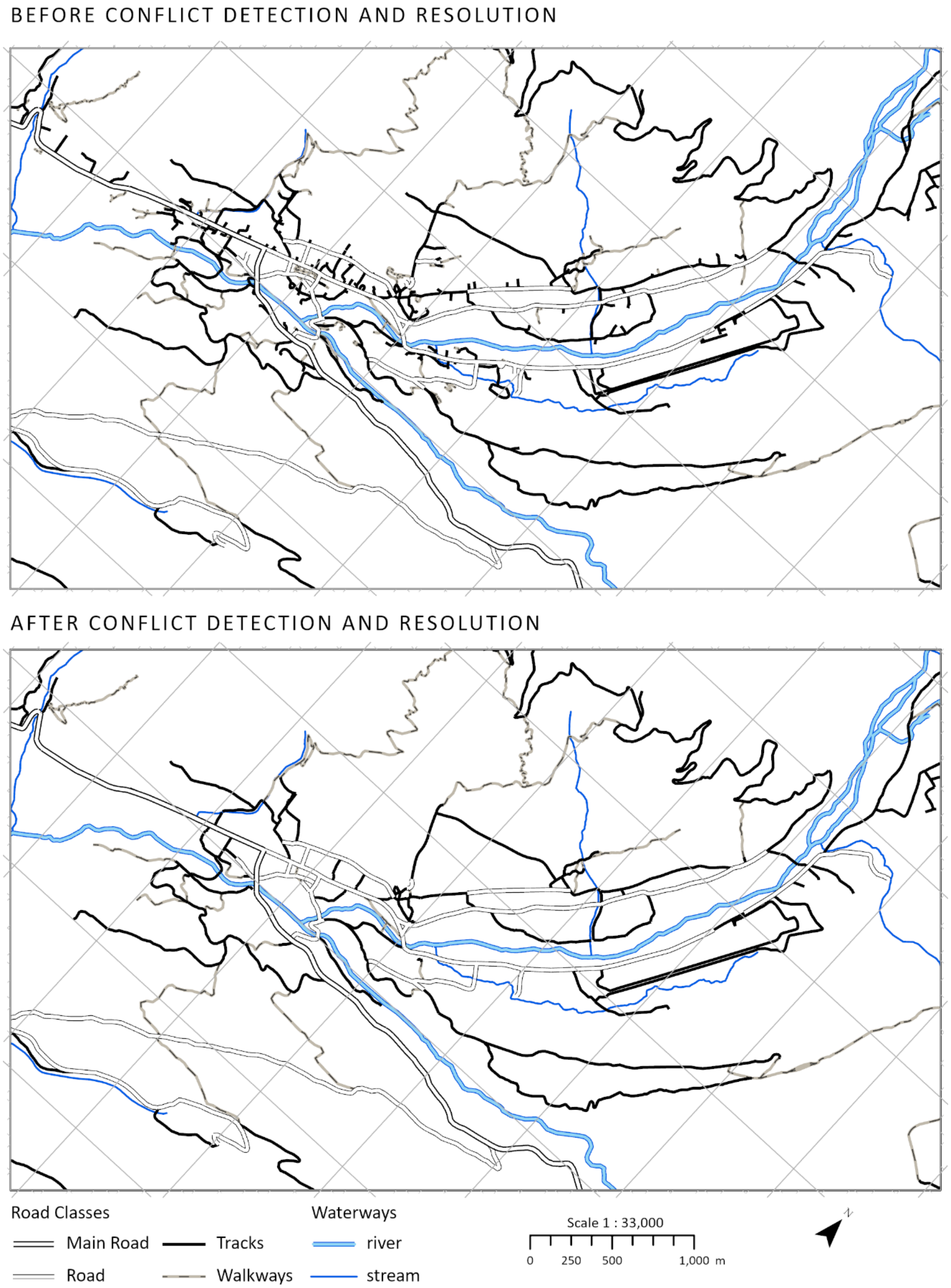


As noted in inset map 2 of Figure 11 the tool does not detect self-overlapping features and is only able to detect like features (two features of the same type and hierarchy) and unlike features (two features of different types like road feature vs river feature – inset map 3). This lack of detection and recognition also exists in the resolve conflict tool as the conflict detection approach is the same. Therefore Section 0 elaborates on a semi-automatic solution to handle self-overlapping conflicts.

4.1.4. Road Conflict detection and Displacement Resolution

The configuration used for the resolve road conflict tools are predetermined in the pre-processing stage as described in section 4.1.1 that discusses the attribute assignment conflict hierarchy for different kinds of linear features. The Propagate displacement tool has two available configurations to carry out displacement. The first is a Solid adjustment protocol most suitable for geometrically shaped roads. Here vertices move the same distance and direction. While the second is an Elastic adjustment protocol, where vertices are moved independently to find the best fit for the road network, with some modifications to the shape of the road when needed. In its implementation an automatic selector was used to select the more appropriate protocol for different parts of the dataset. Inset maps 1 and 3 in Figure 11 like Figure 12 show good examples of the displacement results as well as a comparison of the linear features before and after generalisation. The perspective of the map 'after' generalisation shows the reduction in features from selection and elimination as well as displacement and expansion of features of the remaining features for more balanced representation of the remaining linear features.

Figure 12: Before and After generalisation comparison of linear features.



4.1.5. Using Barriers to resolve self-overlapping conflicts.

A proposed solution to handling self-overlapping has been provided for in this model. To use this solution the user is required to manually identify the features that have that have a self-overlapping conflict and draw a barrier feature midway between the two sides that need to be displaced from each other. Once this barrier feature / data set is available it can be used as an input feature that the model must then find a suitable displacement solution that in effects resolves self-overlapping conflict. In this case the barrier has the minimal symbology/line width and a conflict hierarchy of zero to force the segments in proximity to move away from it.

Figure 13: Proposed solution for self-overlapping features showing the application of barrier features.

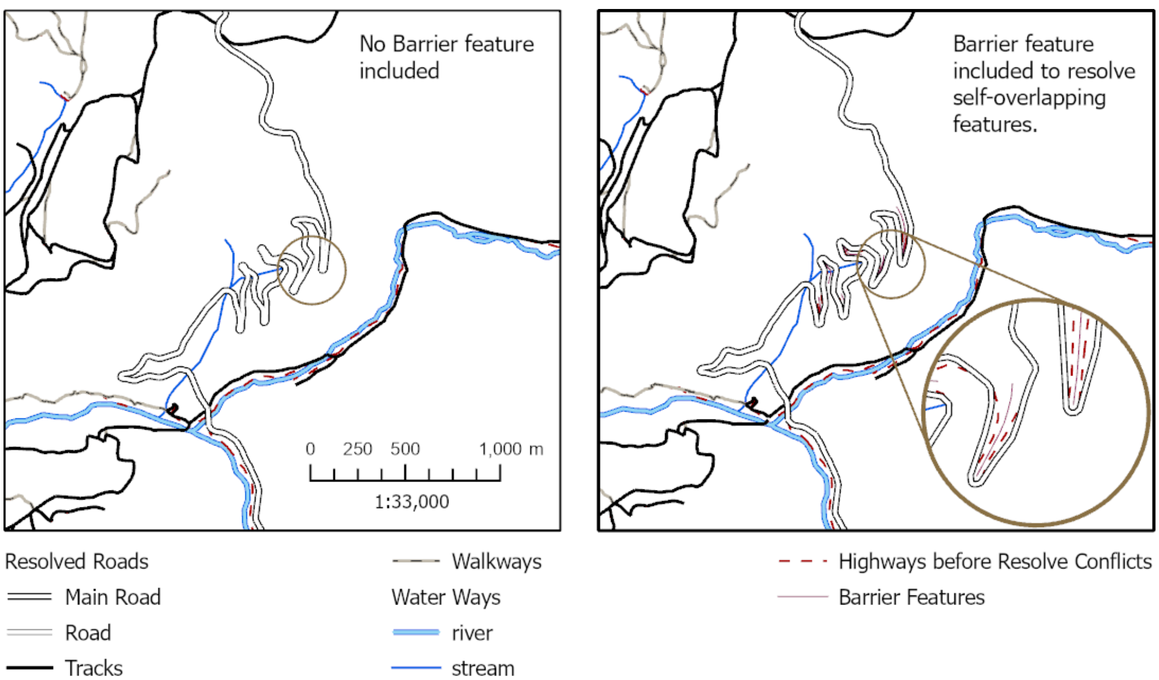
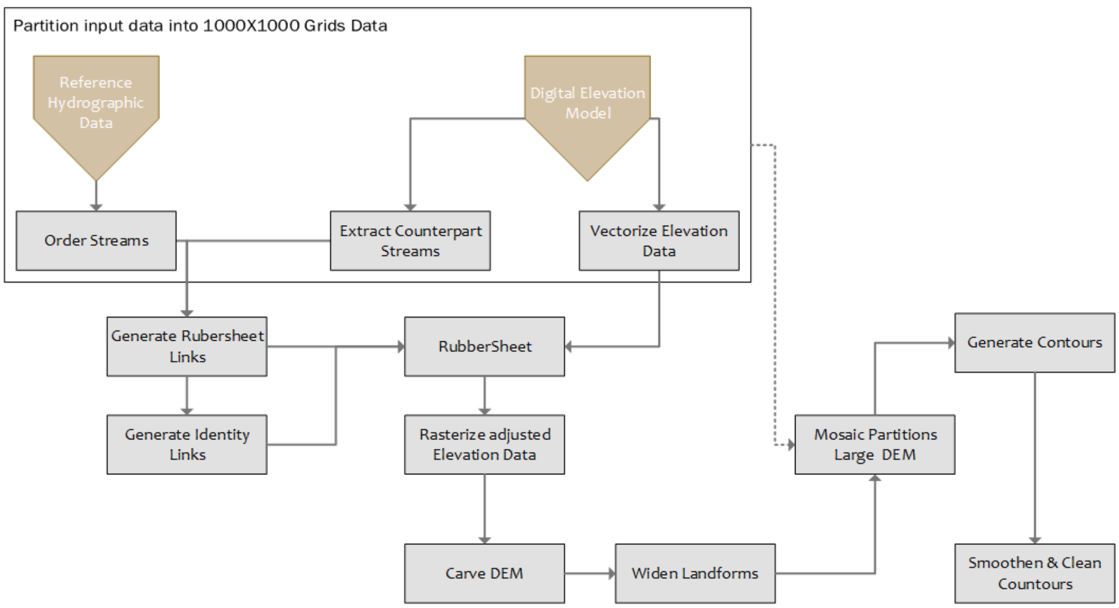


Figure 13 illustrates the results of the self-displacement solution. The first half shows the conflict resolution without the barrier feature, while the second half shows the resolution of conflicts with the barrier feature included. Apart from digitising the feature. The conflict hierarchy is set at 0 in the attributes for the features. This forces the roads to move away from the barrier because they have a lower conflict hierarchy attribute.

4.2. Guide for DEM Conflation in River network matching and contour generation

The DEM conflation approach was adopted as a solution for generating contour lines that match the river network when working with multiple datasets from Heterogeneous datasets. With the methodological explained in section 3.2. The implementation and findings will follow in this section. Figure 14 presents a summarised perspective of the workflow.

Figure 14: Summarised workflow for DEM conflation and matching to Hydrographic lines and contour generation.



4.2.1. Parameters used for Rubber sheeting, conflation links and identity links.

To prepare the conflation links, an extraction of counterpart streams is required from the DEM. Counterpart Stream extraction requires the input of four parameters, namely the catchment radius, minimum flow accumulation, off stream penalty and maximum deviation. As mentioned in the literature the conflation approach adopted here was developed for small scale map generalisation at around 1:500,000 or smaller. In using this approach for a large-scale map the parameters needed to be adjusted to fit the landscape and scale required for the study area. In considering these factors the model was run maintaining the raster grid size of the original 30m elevation data and also applied to an resampled elevation raster at 10m grid pixel size. This would allow for some comparison explore which would be a better pixel size or any other improvement or deterioration to the surface from conflation and scaling it for use at this scale.

Table 5: Parameterisation of Counterpart stream extractions for largescale maps.

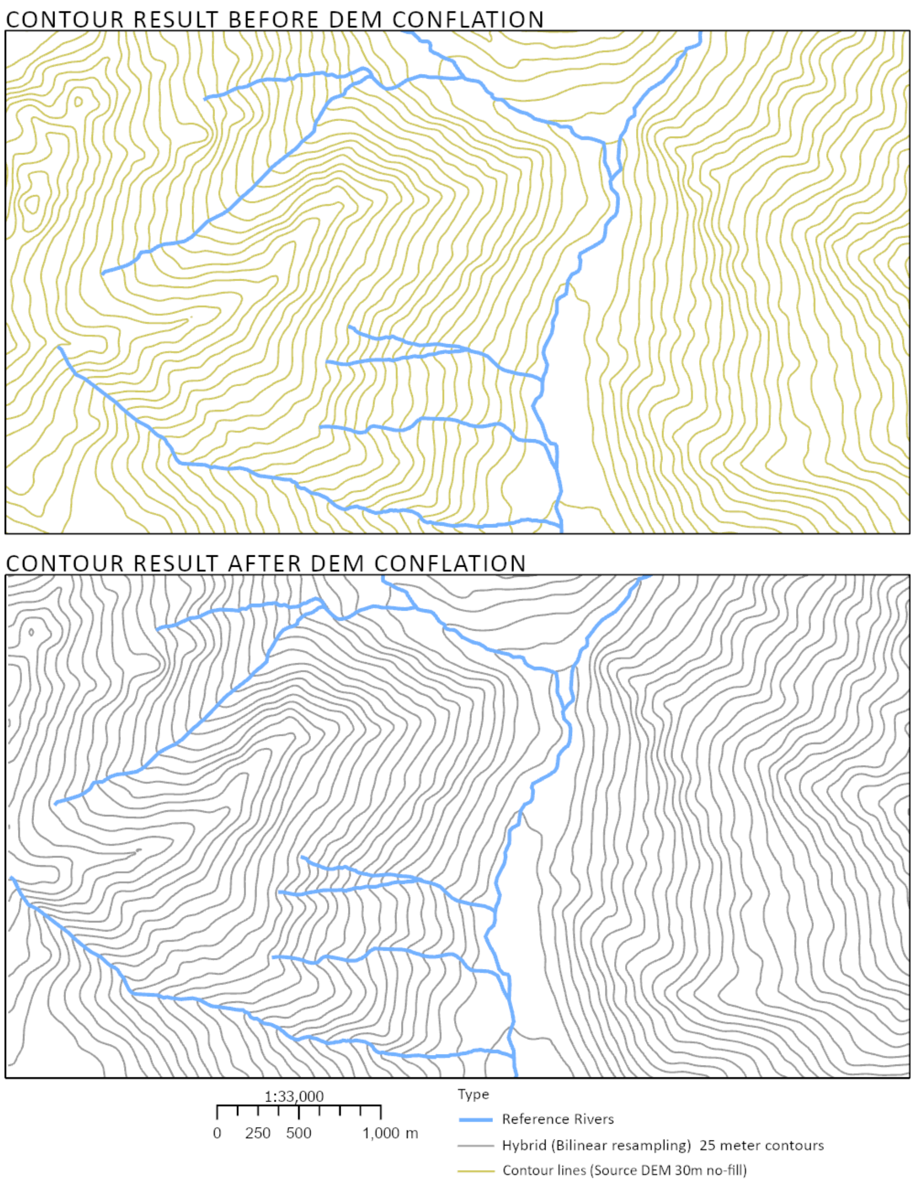
Parameter	DEM 30m resolution	Up-sampled DEM 10m grid size pixels
Catch Radius (*r)*	81	40
Minimum flow accumulation (a)	3	4
Off stream Penalty (w)	30	30
Maximum deviation	81	81 OR 50
Identity Links Buffer Area	90	50
Conflation Distance	90	50

Table 5 shows the combination of parameters used to extract counterpart streams DEM with grid size pixel of 10m x 10m (10m) and 30m x 30m (30m). The core reasoning for this is that the algorithm considered pixel sizes in its formulation and given the multitude of mountain streams of very small diameter, smaller pixel sizes may be more representative in comparison to larger pixels. The remaining tools after extraction of the counterpart streams continue in order as shown in the workflow summary Figure 14.

4.2.2. Contour Generation

For the contour generation part of the model work flow from Figure 14 a simple and standardised approach was adopted for all the conflated DEM surfaces. First the conflated DEMs were smoothed with the Focal statistics tool configured to a 3X3 neighbourhood and weighted with the mean. The next step was to generate the contour at a 25m interval and smooth the line with a 20 meter smoothing tolerance. The smoothing action removed any residual sharp corners for aesthetic value.

Figure 15: Comparison of contour results before and after matching the DEM to the hydrological reference data.



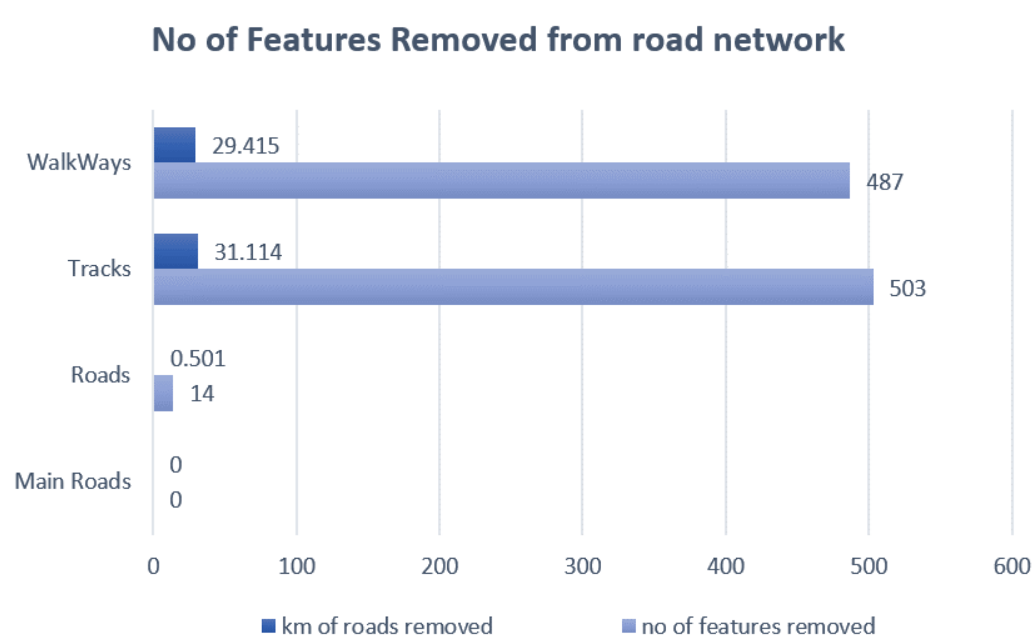
5. Discussion

The two models proposed in this paper show that there are adaptable solutions to resolving generalisation requirements of linear features and contour feature alignment and harmonisation with a rivers course. This section will broadly discuss the successes, failures, of the approaches.

5.1. The Network

Generalising the network is the significant part of the generalisation process from this section it was visible that the highest number of features in dense urban centres were removed. Mostly these features formed parallel paths and short tracks along more important streets and in small neighbourhoods. In low density and isolated areas dangling features were removed especially those not involved in connectivity to other noted. Figure 16 shows the number of features of roads removed from the sample area. Majority of the features were tracks and walkways which make up the two largest components of the route network

Figure 16: Comparison of on the number of feature and kilometres of roads removed from the thinning process.



Accurate topology of the datasets plays an essential role in how effective the network thinning process will be. The inset map in Figure 10 highlighted parts of the line network that needed to be digitised to ensure connectivity of the paths to the parallel roads. Not digitising these short segments would have crowded this section of the map. This is an example of why good quality data is needed and why inspecting the outputs of the modelling process at various stages is valuable to improving the final cartographic product.

5.2. Configuration of the Graphical Conflicts Detection tool.

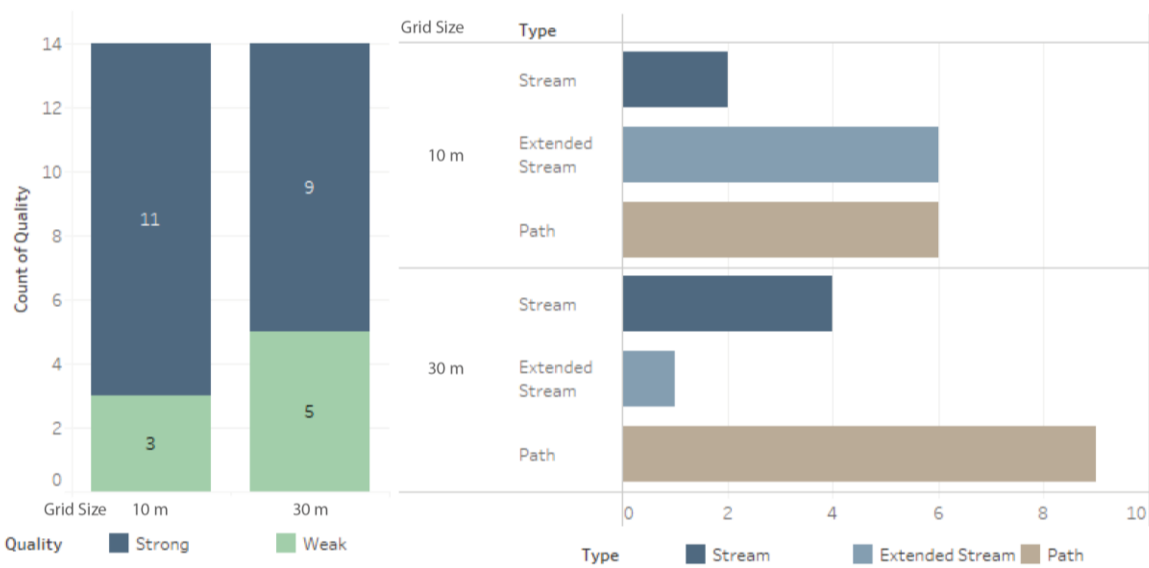
An auxiliary point of caution to note when using the graphical conflict tool is that false positives will exist and not everything detected by this tool is a conflict. This is particularly true when evaluating the route network after resolving road conflicts and displacing features. The reason for this is that first there are immovable features like bridges and intersections to ignore (Figure 11 inset map 1). Additionally, the resolve conflict tool will bring two homogeneous features (same symbology, same type, same hierarchy) that are very near to each other together so that at the print scale they will appear as one feature side by side with no gap in between. This action results in a false positive conflict and can be ignored.

On the other hand, the graphical conflict tool does not detect conflicts that appear from self-overlapping features. Therefore, the user must evaluate the features for these kinds of conflicts and create barrier features to correct this occurrence where needed. This approach can be useful if the source data is refreshed in comparison to manually displacing the features, as it becomes repeatable in the model after the first iteration. Apart from these aspects the tool remains useful to compare blaring conflicts before resolution and or and after resolution when there is concern that a conflict has not been acted on. This is one way to check if both the user and the model understand the data in the model the same way.

5.1. Contour generation and conflated DEMs: The influence of Grid sizes on counterpart stream results.

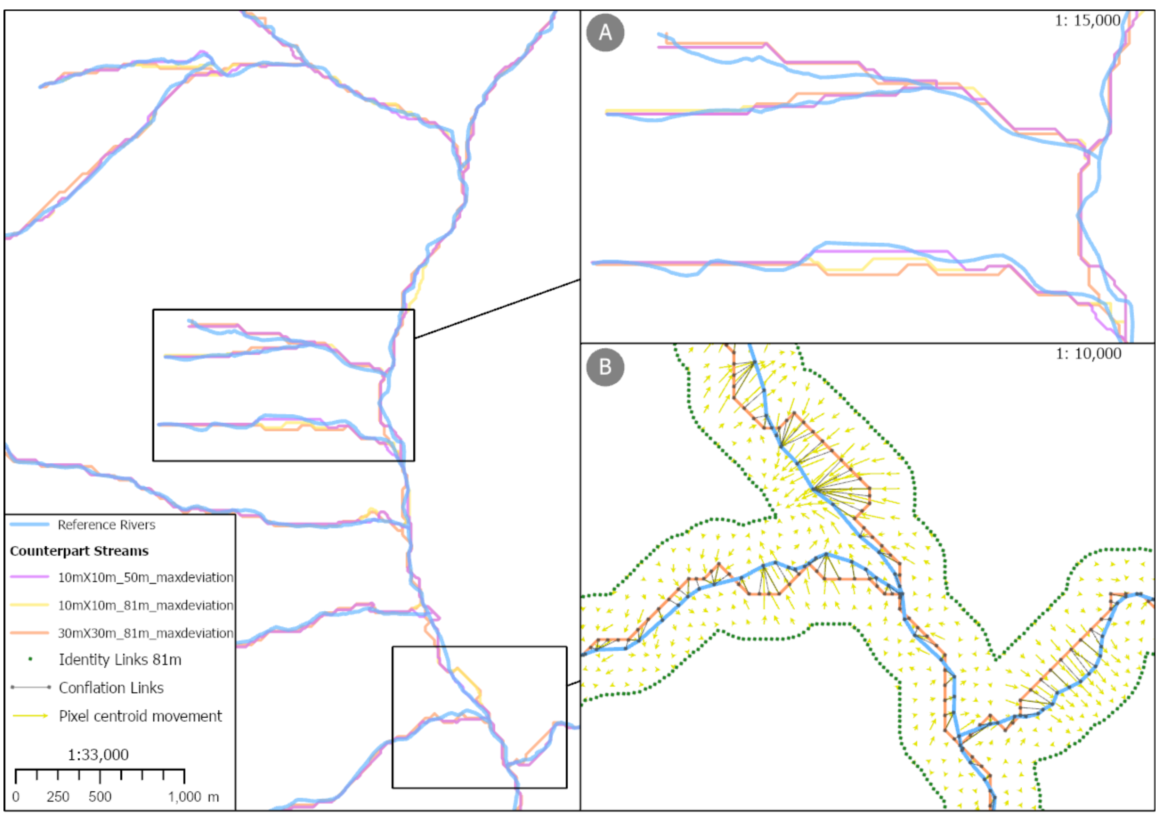
The parameters used for the counterpart stream extractions and the resolution of the raster DEM have a strong influence on the catch radius and minimum flow accumulation. In this case the catchment radius is a multiple of the pixel size and an integer with a the minimum size of 1 pixel. However, using 1 pixel or a catchment radius (r) of 30 creates additional problems. To start it is more difficult to extract a counterpart stream when the catchment radius is very close to the pixel size. For this case a catchment size of 3 pixels or a catchment radius of 81 meters was set. With 81 meters being a large catchment radius relative to the size streams and rivers on the ground, resampling the data can be useful for setting better fitting parameters. For example with a resampled raster of 10m then the catchment radius can be set at 40 meters using a minimum flow accumulation of 4. Analysing the counterpart stream provide an early indicator of the suitability of the parameters selected. Using this data, it is possible to quickly analyse the performance for the sample area.

Figure 17:Quality assessment of detected counterpart streams for different grid sizes



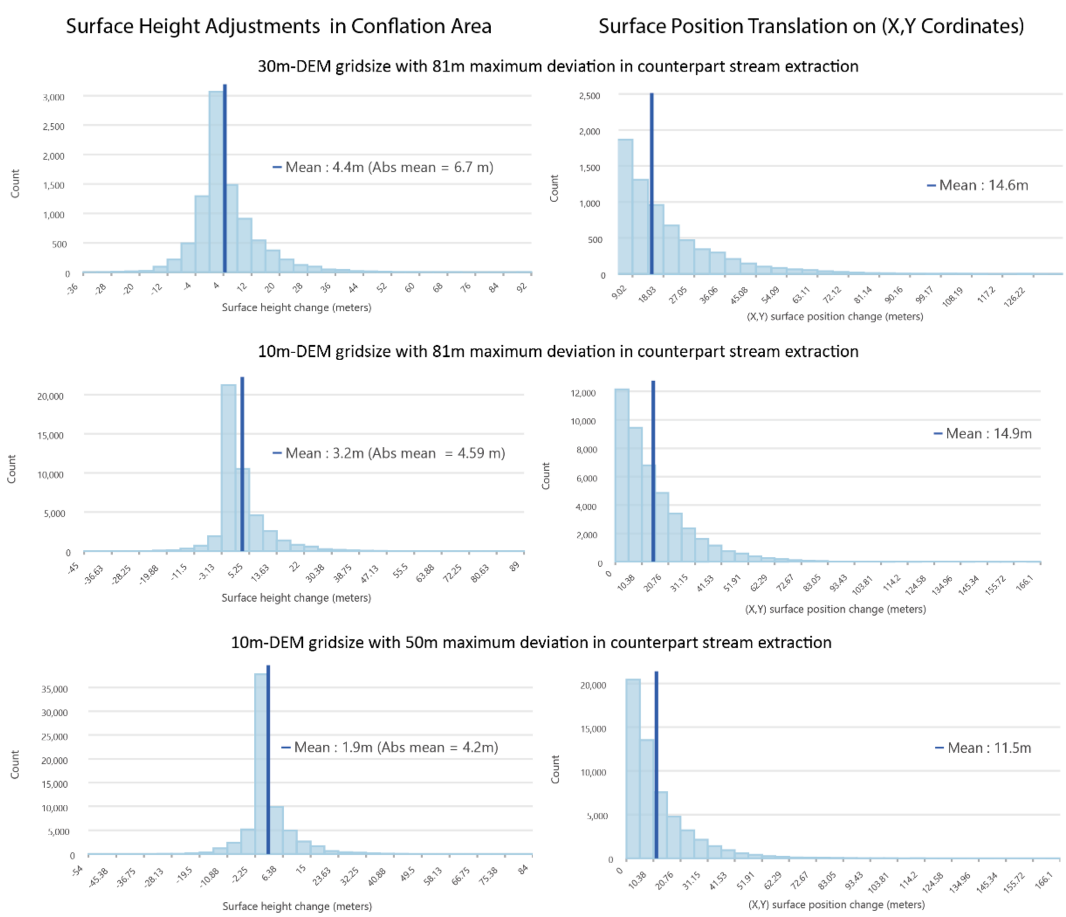
An analysis of the patterns in Figure 17 for the sample shows that selection of counterpart streams improves for the resampled 10m grid raster with a restricted maximum deviation of 50meters as compared to the 30m grid raster with a maximum deviation of 81m. To consider this aspect further Figure 18 compares three different counterpart streams. Illustrating how the combination of the resampled pixels and the restriction on the maximum deviation results in improved counterpart stream extractions. Inset map (A) shows counterpart stream from the 10m DEM with a maximum deviation of 50m is more aligned to the reference hydrographic line. In practical terms for the modelling process this translates to shorter translations in coordinate positions. Inset map B in Figure 18 details the direction and magnitude of translations required for each pixel centroid position for the 30m DEM (yellow arrows). It is clear from this image is that if there is a larger offset between the counterpart stream and the reference stream then the rubber sheeting and conflation of the rasterized elevation data will require larger spatial adjustments in the x,y coordinate directions.

Figure 18: Comparison of Counterpart lines (parametrisation) results with inset of rubber sheeting Components



The increased translations that correlate with the grid pixel sizes and parameter selection of the counterpart extraction process are also visible in Figure 19 when comparing the x,y coordinate position changes and height value changes between the original surface model and the conflated surface models. In the three examples presented the top two charts show an absolute mean height change of 6.7 meters and coordinate change of 14.6 meters when the raster is maintained at the 30m resolution. This reduces to 4.2 meters in height difference and 11.5 meters in x,y translations on average for the resampled 10m DEM and restricted maximum deviation of 50m in the model configuration.

Figure 19: Comparison showing the difference in surface heights and movements of coordinate positions (xy) resulting from DEM conflation including post processing (Carving and Widening) adjustments against the reference unadjusted surface model.



5.2. Examining DEM Conflation cross profiles

The effect of the resampling process in combination with the DEM conflation can be seen by viewing an example profile cut of a valley across the original DEM surface and the conflated surfaces at 30m and 10m resolutions. The 1st and 2nd profile cut for 30m DEMs in

Figure 20 shows the largest block sizes and step variation across the valley. Resampling has the effect of breaking up the blocks into smaller parts as seen in the 3rd profile cut which shows the pattern for the 10m DEM and therefore appears smoother than the first two.

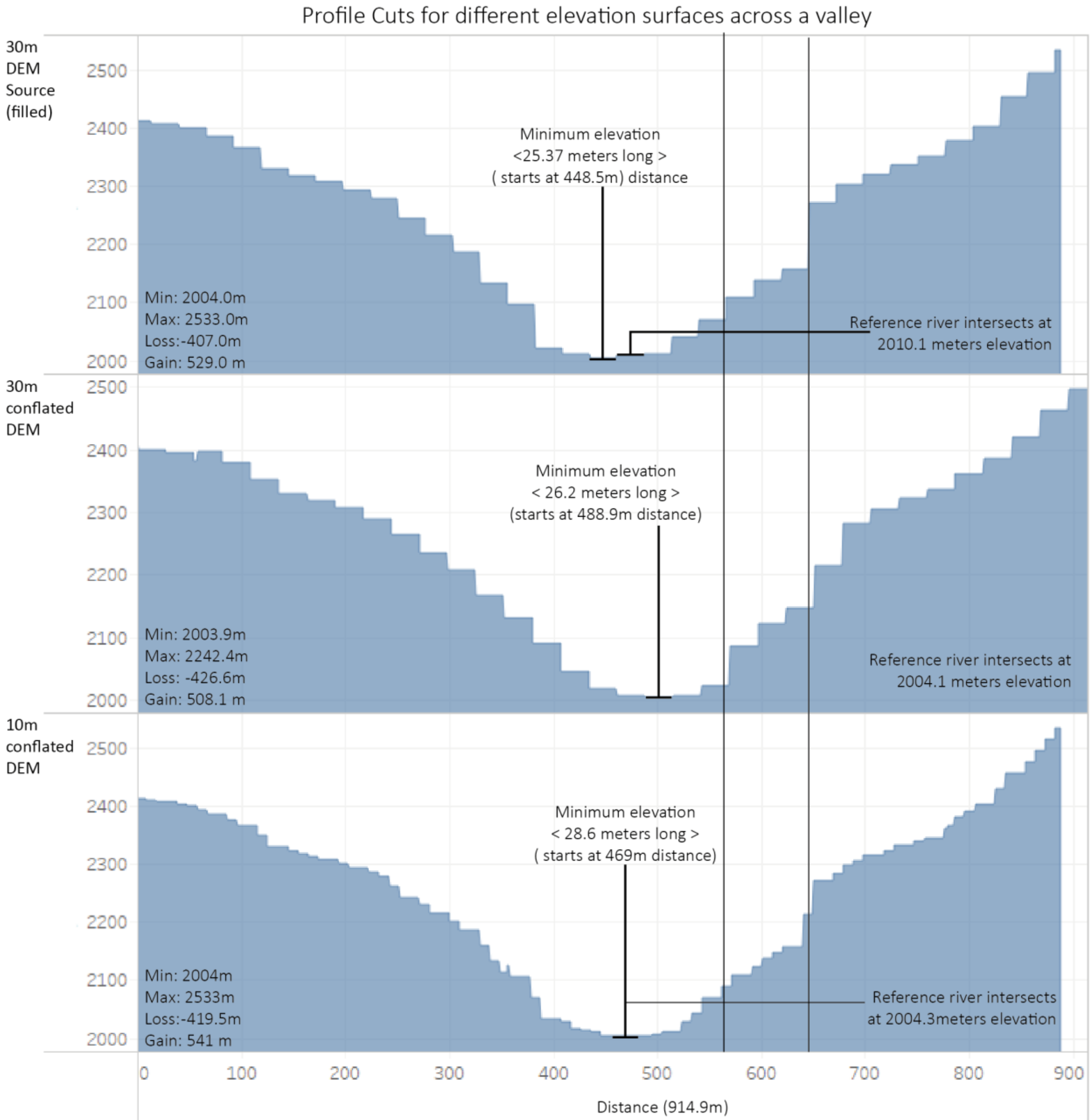
The next visible indicator is the effect of the post-processing stage carving and widening tools on the DEM surfaces. For comparison using the black vertical lines both the conflated surfaces show that they have effectively been widened to enhance the perception of valleys and ridges. For this model only the valleys were directly widened though the tool provides options to additionally emphasize ridges. The carving and deepening of the valley is not directly visible except for a small change in the minimum height of the conflated 30m DEM.

The intersection of the reference river dataset and the DEM surfaces shows that the rivers position is offset along the right bank by a short distance at a higher elevation of 2010 meters in the source dataset which is higher than the actual lowest point in the profile cut. With the river as the reference dataset the modelling and conflation process adjusts the surface within the bounds of the identity links to match the river dataset as shown in the 2nd profile cut.

From the conflation process its visible that for this location the offset is corrected in both conflated surfaces. The intersection with the rivers is approximate at an elevation of 2004 meters. This also shifted the lowest parts of the DEM to the right bank as compared to the original start position in the 30m DEM. For the 30m conflated DEM this is 40 meters further while in the resampled 10m conflated DEM this region starts at 20 meters further.

Widening of the base is also slightly visible with the former conflated DEM widening by 0.83 meters in the 30m DEM and 3.23 meters in the 10m DEM.

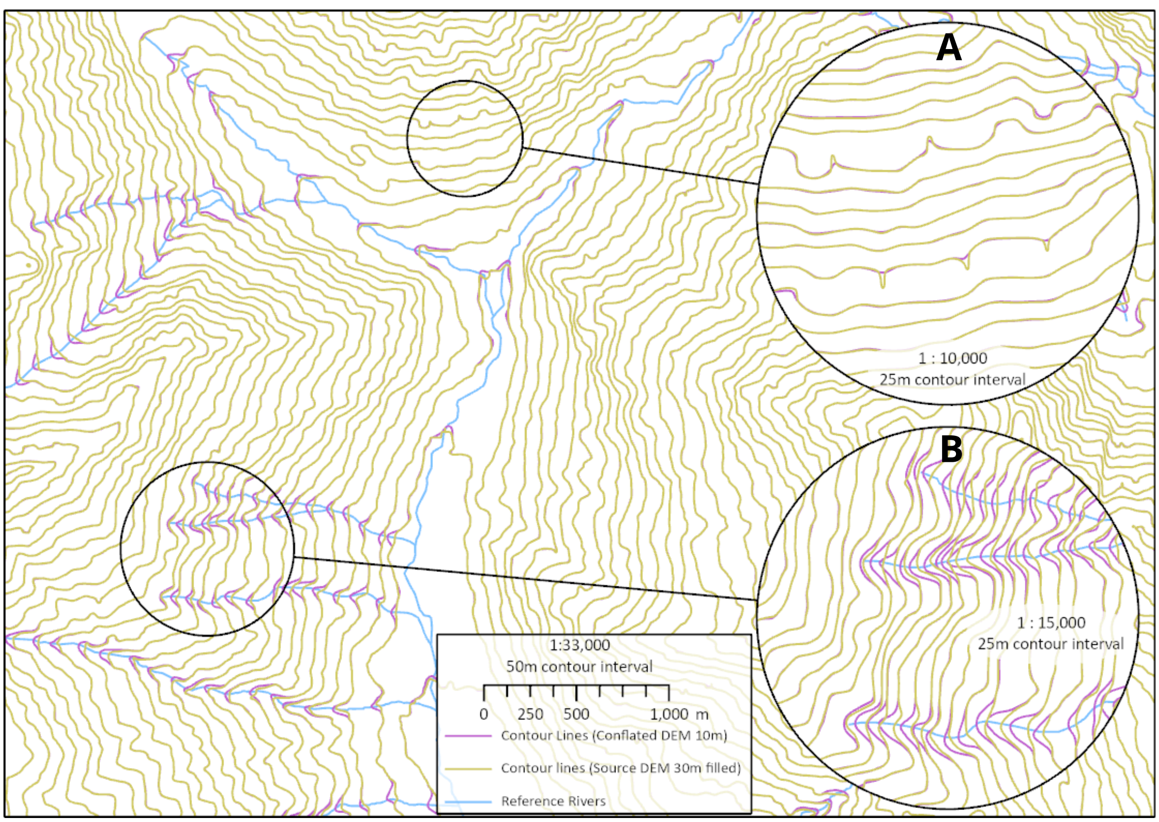
Figure 20: Comparison of profile cross sections for a valley in the sample area across three surface elevation models



5.3. Examining contours generated from conflated DEM process compared to the Source elevation raster.

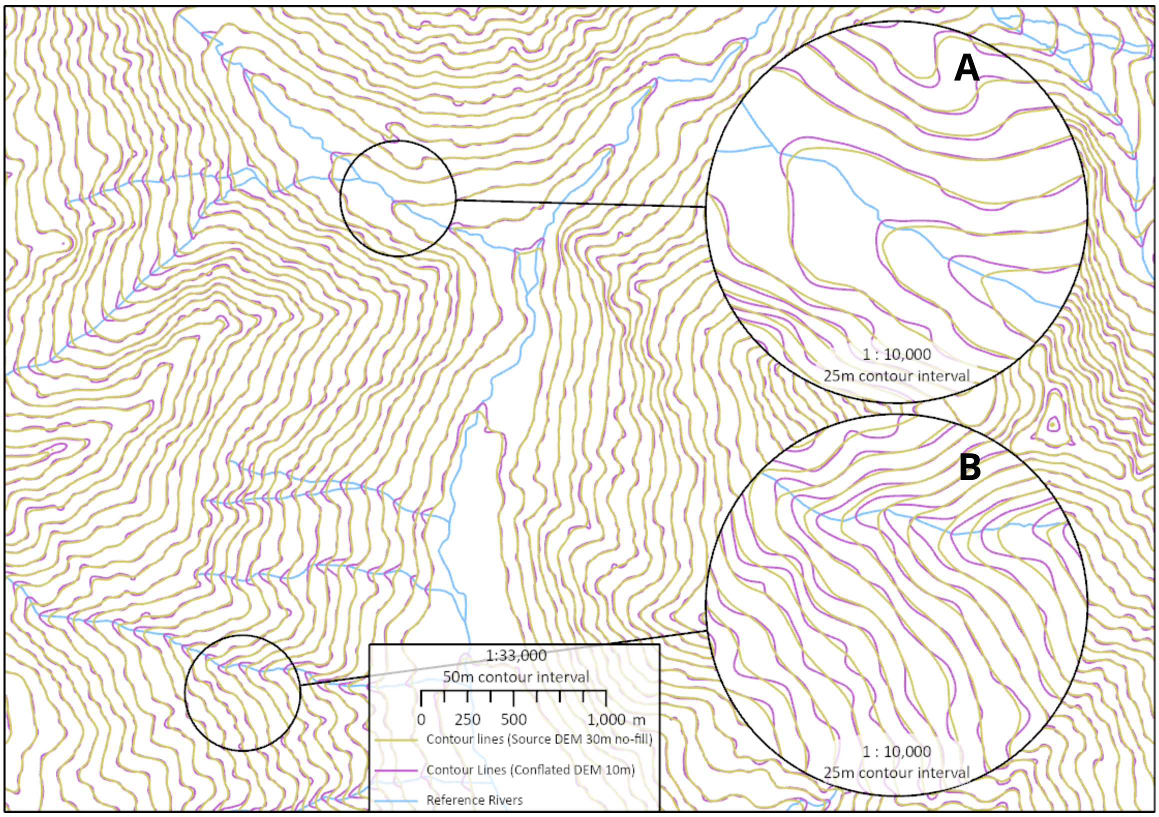
Contour generation is the last part of the modelling process. To examine the results comparisons are made between contours from the original 30m DEM and contours from the Conflated DEMs. In this first illustration Figure 21 the contour results from the resampled 10m conflated DEM are visible in pink. This shows exactly where the conflation process alters the and the contours reflect this concentrated change along river valleys. Although these to results match fairly well. The contours are low quality because they show artifacts from the both the conflated 10m DEM surface and also the 30m DEM surface. Inset (A) shows a close up of these artifacts which are repeated in other areas.

Figure 21: Comparison of contours from resampled 10m Conflated DEM and 30m Source DEM with filled sinks



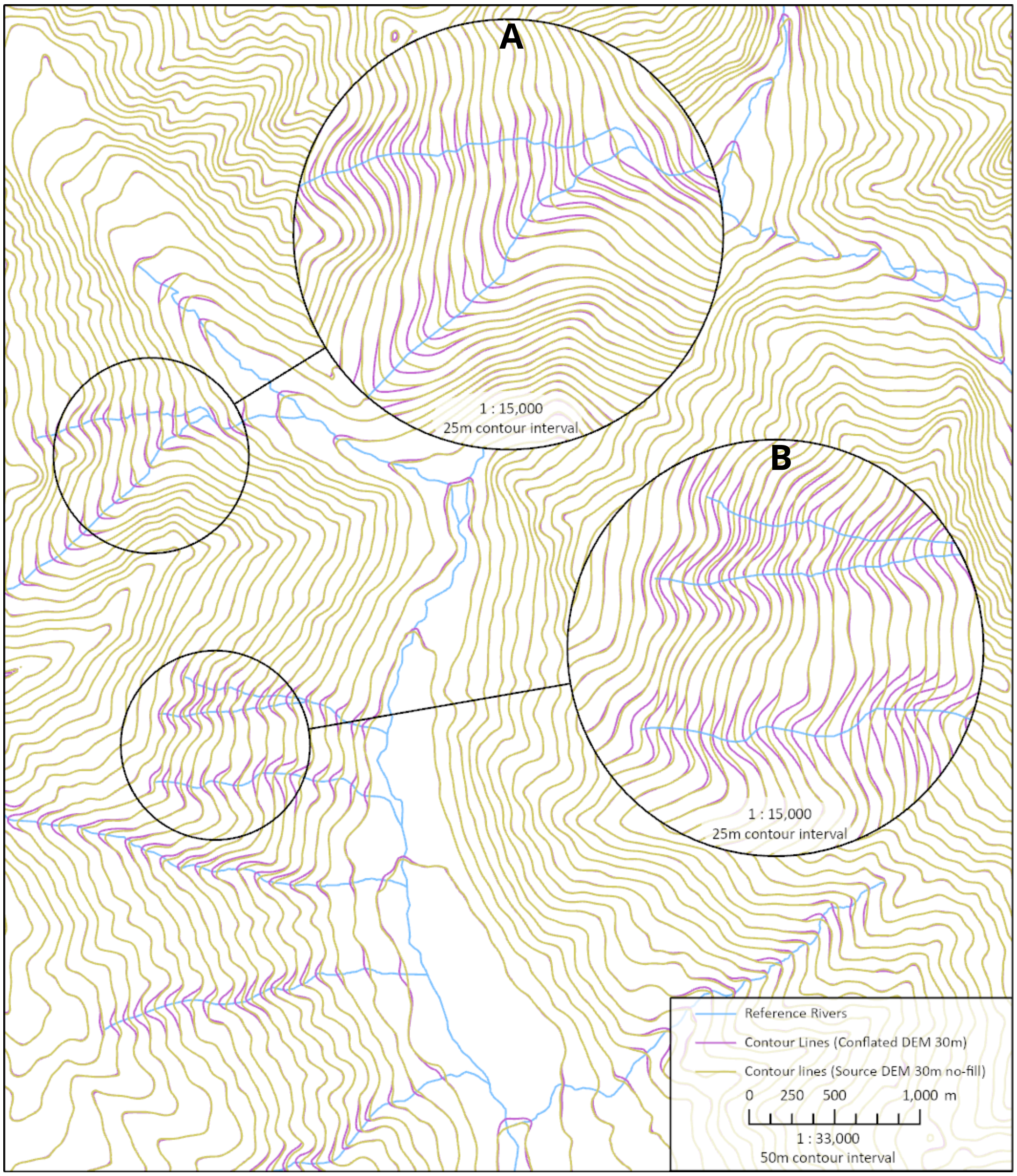
Although the DEM surface was additionally smoothened and averaged using a focal statistics tool, the effect was not strong enough. Additionally, the modelling applied to the 30m DEM in the conflation process has a strong effect including in areas outside the identity links which should not have changed but appear to change. This can be seen in Figure 22.

Figure 22: Comparison of contours from resampled 10m Conflated DEM and 30m Source DEM with unfilled sinks



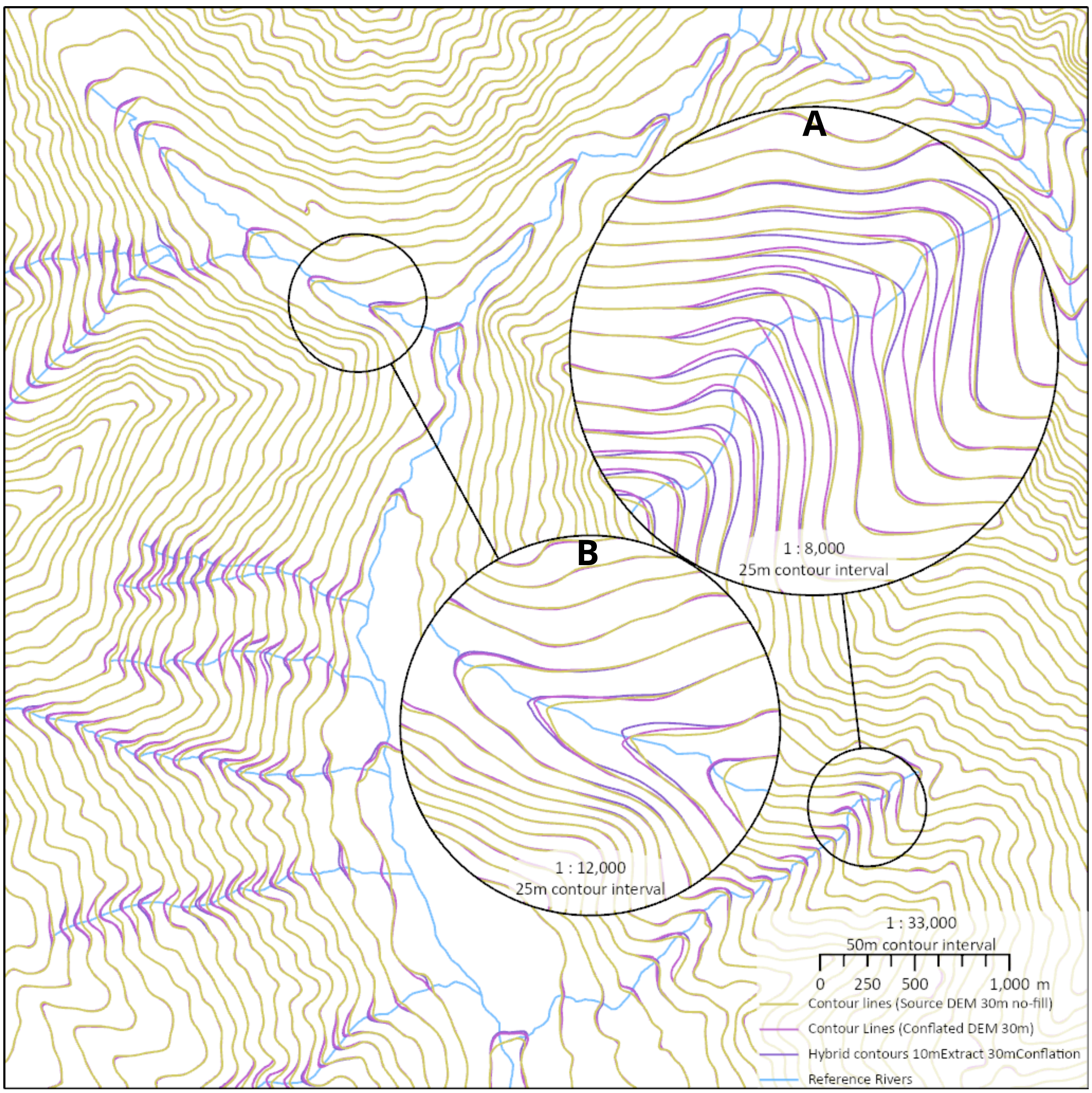
Another comparison is from Figure 23 which compares the contours from the conflated 30m DEM with source 30m DEM. In this example the conflated contours lines in pink show good adjustment to the river course in the valley and no movement in areas outside the identity links. In this situation the effect of filling the surface model to generate the flow accumulation model is minimized hardly visible. This shows that the larger grid size performs better in this way. In some areas although the surface has been adjusted to fit the river better it is not 100% perfect at all contour and river intersections. This is perhaps due to the grid size of the DEM. One case of this is magnified in the inset map (A). At varying lengths of 50 - 100 meters the adjustment of the contour's lags the meandering river before it corrects itself and aligns to an improved central position.

Figure 23: Comparison of contour lines generated from 30m source DEM and 30m Conflated DEM with 81m maximum deviation.



Based on the findings in this section, and the assessment of the counterpart stream extractions. A redesigned model was predicted to improve the overall result even further. This hybrid approach uses the counterpart streams of the resampled 10m raster as an input dataset for the conflation process of the 30m raster. With the aim of achieving the best of both models. Figure 24 shows the effective result of this hybrid result.

Figure 24: Comparison of contours from the source 30m DEM, 30m conflated DEM and hybrid 10m counterpart stream extract combined with 30m conflated DEM.



While the change is slight the positive side of the hybrid model is visible, particular in the inset map (A). In this example, this valley in the conflated 30m DEM strayed even further away from the rivers course than even in the source DEM. The hybrid model result in purple does not and can be seen to maintain a correct attachment to the rivers course and has a more consistent result overall. In general, where there were agreements in the extracted streams at a grid size resolution of 10m and 30m then there was no change in the result. When the extracted counterpart streams differed significantly then this variation is reflected by the position of the contours. The hybrid contours the most improved results even though a few times it may vary from the ideal location as shown in the inset map (B). Fortunately, this imperfection is not easily discernible at the print scale for the alpine map 1:33000. Showing the solution will work at this and smaller scale but an alternative method of aligning the contours to rivers would be required for larger scale maps. These examples show the importance of testing iteratively to optimise the parameters used for the counterpart stream extraction as well the value trying to identify an optimal resolution for the elevation surface if one is not readily available.

6. Conclusion

This thesis had three main objectives. The first objective was to identify and implement generalisation approaches for linear features required for a small-scale print map. The main generalisation requirements identified included network generalisation and solutions for coalescence conflicts. This paper presented a solution for these requirements using ArcGIS Model builder, that could successfully generalise a variety of linear features, such as roads, paths, tracks, water way features (river & streams) , as well as linear based polygon features like river banks.

The second primary objective was to find a solution for harmonising contour lines with the course of rivers from separate data sources. The implemented model adapts a python-based approach for DEM conflation to first create new elevation surface with spatially adjusted valleys that have improved alignments rivers course and are therefore hydrological aligned between the two features. Then second, with the harmonised elevation data generate smoothed and improved contours that are better representative of the rivers path. The results presented in this paper show that it is possible to succeed using this approach with several constraints that will influence the outputs.

First, the resolution of the source DEM is important relative to the features on the ground. This will also directly impact the scale that this approach can be applied to. The larger the scale requirements are, the higher the resolution of the DEM that will be required for this solution to work. At a scale of 1:33,000 the modelled solution improved the dataset with close margins. At even larger scales as in many of the examples ie 1:15,000 the flaws and limits of this approach will start to show. Therefore, the source dataset and target output scale will limit when this approach can be a validly applied.

An additional challenge with this solution is the limitations on the amount of data it can process. In its basic form as implemented there a limits not only to the ground area that can be covered in a single run but also to the and number of streams that can be identify. This limit is also intrinsically linked to pixelsize in the elevation dataset as a higher resolution dataset will also increase the amount the computation load and therefore it will take longer to run. Early indication is that this is limited to approximately 1000 x 1000 pixels. Therefore, the main recommendation to improve this approach particularly for large scale mapping requirements would be to improve this limitation to a much larger area or redesign the model in ways that adopt cartographic partitioning capabilities as implemented in ArcGIS pro.

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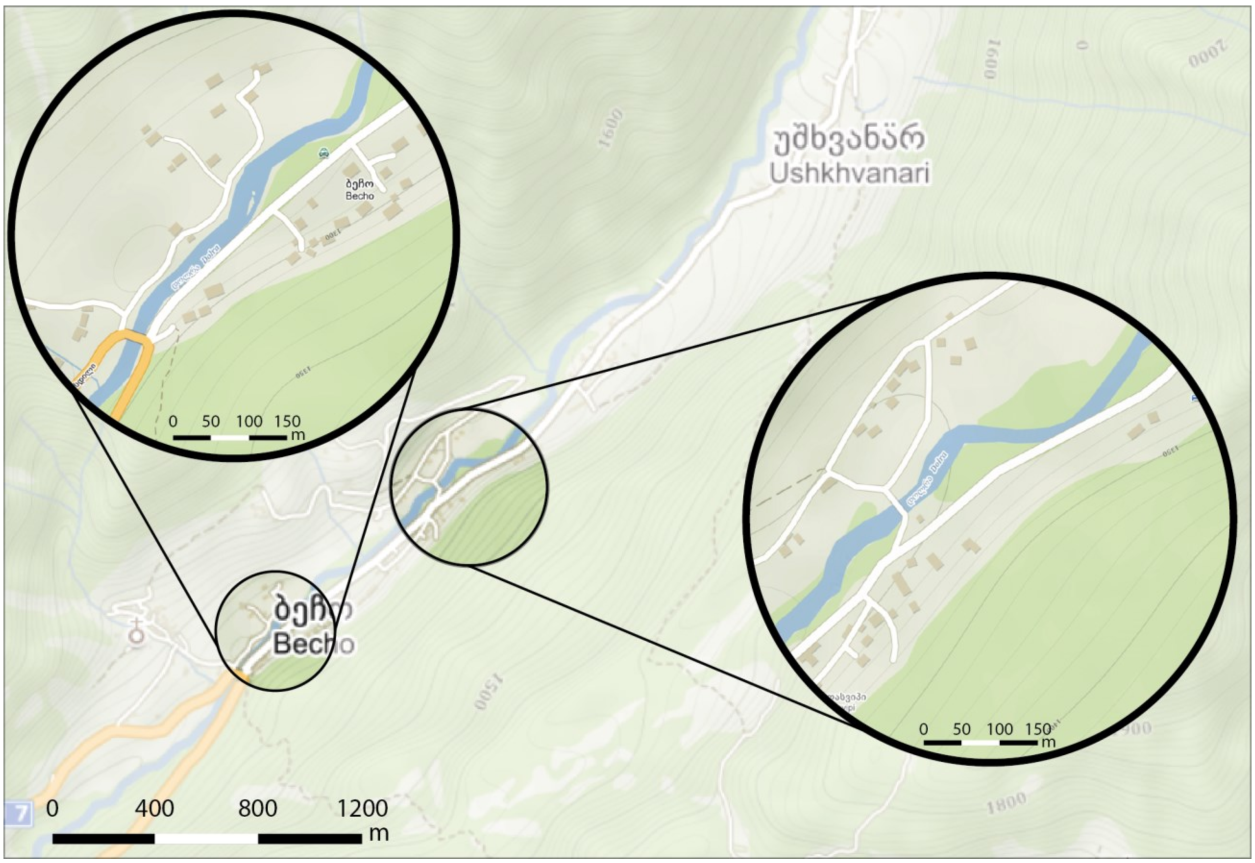
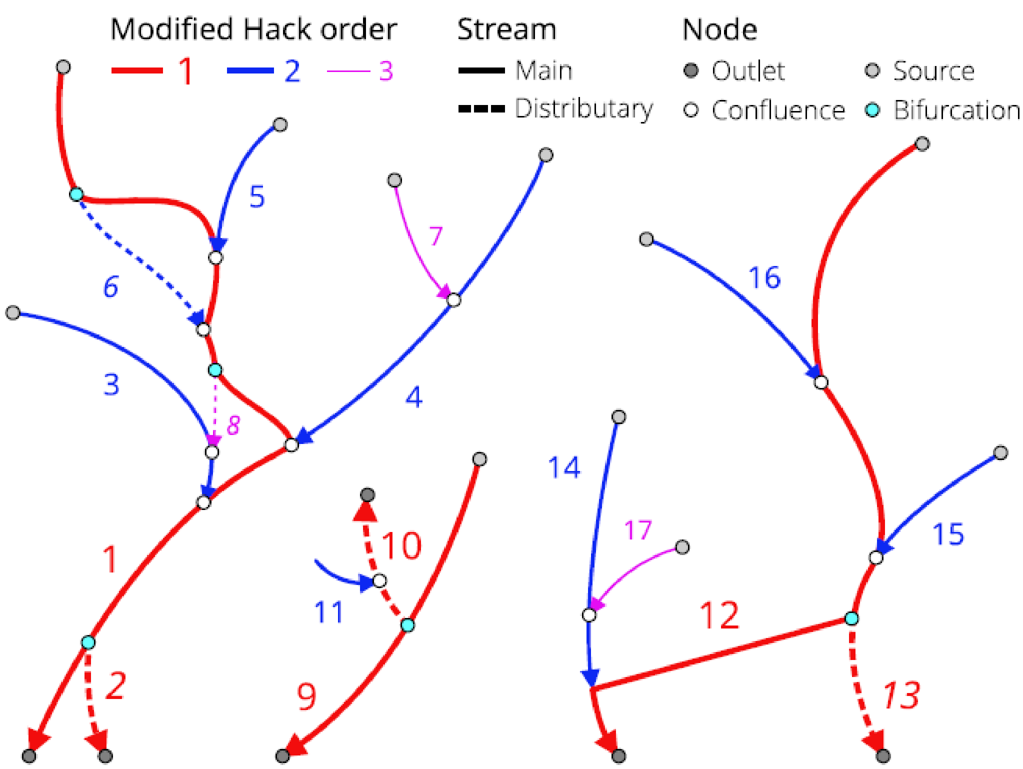
8. Appendices

Appendix 1. Example of River and Road conflicts showing coalescence between different feature types.



Source: *Mapy.Cz*, 2020

Appendix 2. Reference Hydrographic Lines arranged according to the Modified Hack Ordering



Source: Samsonov, 2020, p. 8