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An Assessment of the Lengths of Permanent, Intermittent and Ephemeral Streams in the Auckland Region

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An Assessment of the Lengths of Permanent, Intermittent and Ephemeral Streams in the Auckland Region

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Prepared for
Auckland Regional Council

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1 Executive Summary

Streams in the Auckland Region have been subject to degradation from historical land use change and urban development. In order to effectively manage such streams, Auckland Regional Council (ARC) requires an accurate estimate of the total length of small streams in the region. Current estimates based on 1:50 000 topographic maps underestimate total stream length, particularly because the maps consistently omit streams less than 500 m long. Streams are classified by ARC as permanent (continuous flow and/or persistant pools), intermittent (seasonally flowing within defined stream banks) or ephemeral (flow for short periods of time following rain events), and they are accorded a different levels of protection under the Air, Land and Water Plan. Therefore, the length of each stream type must be known in order to ensure effective management. The aims of the current report were to produce a more accurate estimate of the total length of permanent, intermittent and ephemeral stream in Auckland Region, and to classify the total length of permanent streams by Strahler stream order.

To calculate stream length, we used terrain analysis of a DEM (digital elevation model) based on a LiDAR (Light detection and ranging) survey to produce a stream channel map. This was done in ArcGIS 9.3 using the Hydrology Tools in the Spatial Analyst toolbox. The model was calibrated using field survey data of stream lengths from 26 catchments in four hydrogeological areas across the Auckland Region (Wilding and Parkyn 2006).

Results indicated that there are 16 650 km of permanent stream, an additional 4480 km of intermittent stream and an additional 7110 km of ephemeral stream in Auckland Region. At the 95% confidence level, the range for permanent streams is 14113-20190 km, for permanent + intermittent streams is 17340-31620 km and for permanent + intermittent + ephemeral streams is 25520-37820 km. Of the 16650 km of permanent stream, 8753 km is first-order, 4262 km is second-order, 2121 km is third-order, 1003 km is fourth-order, 372 km is fifth-order, 122 km is sixth-order and 16 km is seventh order.

Because field data were scarce, we used all the data available to derive the threshold contributing areas, leaving no extra field data with which to validate the model. Therefore we advise always reporting the confidence limits along with the stream length values in order to provide robustness to the estimates.

Our estimate for permanent streams is 77% greater than that shown by 1:50 000 topographic map blue lines, despite the fact that topographic map blue lines include some intermittent reaches.

The greatest source of uncertainty in the estimates is due to the difficulty in choosing an appropriate "contributing area" to calibrate the model. Further field surveys of actual stream lengths in different hydrogeological areas would be required to reduce this source of uncertainty. Artefacts from the channel mapping procedure are believed to have produced relatively small errors.

The stream network was intended primarily to estimate the total length of permanent, intermittent and ephemeral streams in Auckland Region, not to show the exact locations of these three stream types in the landscape. Therefore a great deal of caution must be exercised if the stream network is used to locate specific stream reaches.

2 Introduction

Current estimates of total stream length in Auckland Region are based on 1:50 000 topographic maps. However these maps underestimate total stream length, particularly because, according to a technical specification, they consistently omit streams less than 500 m long (National Topographic/Hydrographic Authority, 2003). In a field survey of 32 sample catchments in Auckland Region, Wilding and Parkyn (2006), found that of 21 km of permanent, intermittent and ephemeral headwater streams surveyed, only 8.5 km were shown as blue lines on 1:50 000 topographic maps. The aim of the present study was to extrapolate the results of this field survey to obtain total lengths of permanent, intermittent and ephemeral streams for the whole Auckland Region. A previous report (Storey *et al.*, 2008), which surveyed a number of possible methods to estimate total stream length using the data of Wilding and Parkyn (2006), recommended a stream channel mapping approach based on terrain analysis in Geographical Information Systems (GIS).

Channel mapping by terrain analysis is now widely used as a basis for hydrological models and a range of applications in cartography, geomorphology and water resources management (e.g., Tarboton and Ames, 2001; Giannoni *et al.*, 2005; Heine *et al.*, 2004). In New Zealand it has been used to produce the River Environment Classification (REC; Snelder *et al.*, 2004), which is a national-scale stream map used extensively by water resource managers. The REC was not suitable for this analysis, however, as it is based on a digital elevation model with 30 m resolution, and stream channel initiation occurs at minimum catchment areas of 20 ha. Since Wilding and Parkyn (2006) it has been known that channel initiation in the Auckland Region typically occurs in much smaller catchments, as small as 1 hectare or less.

The accuracy of channel mapping by terrain analysis is the subject of many studies (e.g., Tarboton and Ames, 2001; Heine *et al.*, 2004; Giannoni *et al.*, 2005), and depends on several factors. First, an accurate, high-resolution digital elevation model is essential for detecting landscape features, such as the transition from hillslope to valley bottom, that determine the location of stream channels (Montgomery and Foufoula-Georgiou, 1993). Second, the method used to determine the possible directions of flow paths (D_8 vs $D_{infinity}$), also has an influence on the location of stream channels in the digital network (Tarboton, 1997). Third, and possibly the most difficult issue to resolve, is where in a catchment a stream channel will be initiated (e.g., Montgomery and Foufoula-Georgiou, 1993). A number of different methods have been proposed to identify the point at which diffuse overland flow becomes channelised and a stream appears (Heine *et al.*, 2004; Lindsay, 2006). These include “valley recognition” methods that examine changes in valley landform to indicate the start of stream channels, and “channel initiation” methods that simulate overland flow and the processes involved in channelization to locate channel heads (Lindsay, 2006). Different channel initiation methods relate to different theories about which forces are most important in driving the transition from diffuse overland flow to channelised flow in particular catchments (Montgomery and Foufoula-Georgiou, 1993; Heine *et al.*, 2004). Finally, the accuracy of channel mapping depends on taking into account some of the catchment characteristics that affect the position of the channel head, such as geology, land slope, rainfall and land use (Montgomery and Foufoula-Georgiou, 1993).

Despite the debates about the accuracy of different techniques, and the number of factors that potentially influence stream channel initiation, we decided to proceed with a GIS-based channel mapping technique. The high accuracy (0.5 m vertical accuracy) and resolution (2 m) of the LiDAR (Light detection and ranging)-based DEM, and the fact that we were interested only in stream length and not stream location meant that our results were not as vulnerable to error as some of the examples cited above. Furthermore, GIS-based channel mapping was the only practical approach we could identify for calculating total stream length in Auckland Region.

3 Methods

3.1 Definitions of permanent, intermittent and ephemeral stream

For the purpose of this report, we defined permanent, intermittent and ephemeral streams according to the following definitions (Auckland Regional Council, in prep.):

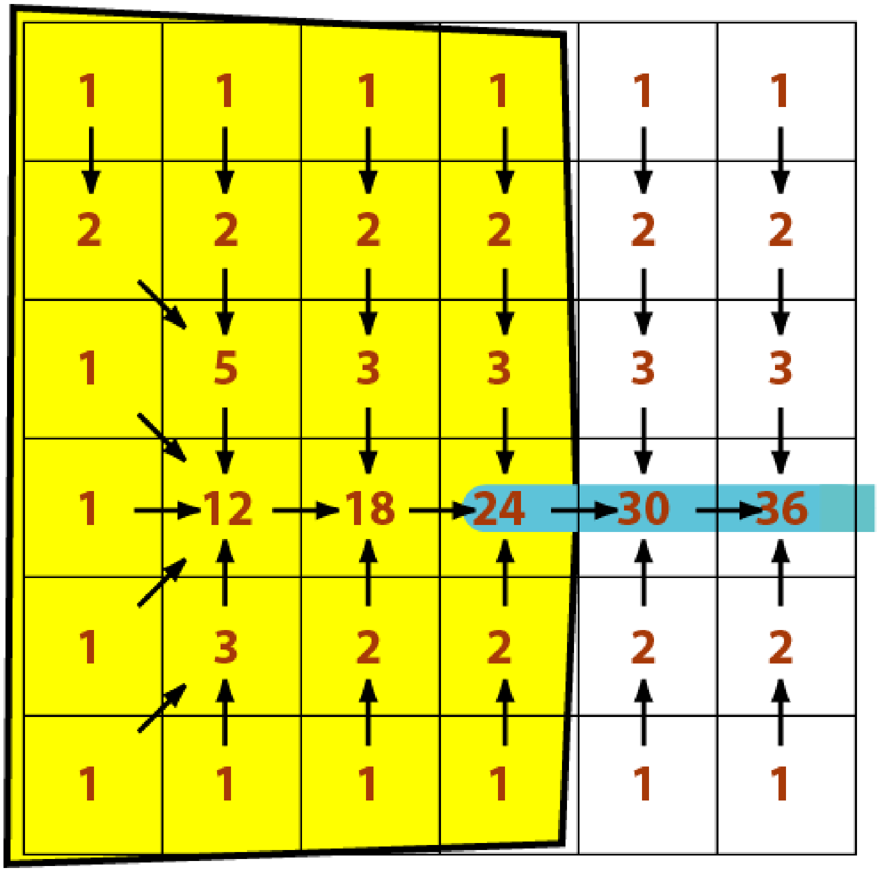
> **"Permanent river or stream**
>
> Downstream of the uppermost reach of a river or stream which meets either of the following criteria:
>
> a) has continuous flow; or
>
> b) has natural pools having a depth at their deepest point of not less than 150 mm and a total pool surface area that is 10 m^2 or more per 100 m of river or stream length;
>
> The boundary between permanent and intermittent river or stream reaches is the uppermost qualifying pool in the uppermost qualifying reach.
>
> **Intermittent stream**
>
> A stream that does not satisfy the criteria for a permanent nor ephemeral Stream and is characterised by having intermittent flow and/or intermittent pools for the majority of the time and is confined in a channel with defined banks
>
> **Ephemeral stream**
>
> A stream that does not satisfy the criteria for a permanent nor intermittent Stream and is characterised by an area of land where there is concentrated flow for short periods of time during and/or after rainfall, but is otherwise dry for most of the time. For the purposes of this definition, the concentrated flow is not confined within a channel with defined banks."

3.2 Stream channel mapping procedure

To calculate the total length of permanent, intermittent and ephemeral streams in Auckland Region, we used a Geographic Information Systems (GIS)-based stream channel mapping approach. Stream channel mapping involves creating a spatially-explicit digital stream network that matches what may be seen from aerial photos or on the ground. It requires GIS to analyse the land surface of a digital elevation model (DEM) and place stream channels in valleys. We chose to use ArcGIS 9.3 as the platform for this analysis and the "Hydrology Tools" in the Spatial Analyst toolbox in preference to other channel mapping software available, such as TauDEM (Tarboton, 2003). In test runs, TauDEM gave similar results to Hydrology Tools, but produced some unrealistic artefacts, due to the flow separation method. Because we were using a high-resolution LiDAR DEM we considered the D8 method (as implemented in ArcGIS) more reliable, since no flow separation is needed for high resolution DEMs. The channel mapping process (Figure 1) involves several steps, each using a separate Hydrology Tool, as follows:

1. The "Fill" tool is used to correct sinks in the terrain surface that might disrupt flow paths.
2. Overland flow direction (direction of steepest descent) is calculated for each grid cell in the DEM with the "Flow direction" tool. This tool is based on a D_8 algorithm.
3. Once flow direction is defined, the movement of water from one cell to another down a slope can be determined. The accumulation of flow in each cell from ridge tops to valley bottoms is calculated using the "Flow accumulation" tool. Flow accumulation is equivalent to a "contributing area", i.e., an area of the catchment that contributes flow to a particular cell.
4. A threshold is set such that cells with flow accumulation (contributing area) above a defined value are deemed to represent stream channels. The "Raster calculator" is used to convert the flow accumulation raster into a raster of channel/no channel using this threshold.
5. The resulting stream network raster is analysed to define the junctions between streams and the stream reaches, or "links" that connect the junctions. Each stream reach is defined and assigned a unique number using the "Stream link" tool.
6. Each of the stream reaches is converted from raster format to a line feature using the "Stream to feature" tool.
7. The length of each stream reach is calculated and added to produce a total stream length for a defined area.

Figure 1:
Example catchment grid (raster) showing the sequence of steps in Hydrology Tools. 1) Each cell is given a flow direction (black arrows); 2) flow directions are used to calculate a flow accumulation for each cell (numbers in cells), defined as the cell's own value of 1, plus the value of all cells flowing into it; 3) a threshold flow accumulation is set for the initiation of a stream channel (in this case 23). The threshold flow accumulation defines a threshold contributing area (here, the 23 shaded cells) which is equivalent to the catchment area above the channel head.



1	1	1	1	1	1
2	2	2	2	2	2
1	5	3	3	3	3
1	12	18	24	30	36
1	3	2	2	2	2
1	1	1	1	1	1

The only input data required to run the analysis are the digital elevation model and the threshold contributing area to initiate stream channels. The DEM used here was derived from LiDAR surveys commissioned by Auckland Local Government Geospatial Information (ALGGi), a consortium of Auckland Regional Council and the seven territorial authorities in Auckland Region. The LiDAR surveys were flown in 2006, and the DEM made available in October 2006. Urban areas were surveyed using one point per 2 m^2 with 0.25 m vertical accuracy, producing 0.5 m interval contour lines, from which was derived a regular grid DEM with one point per 4 m^2 (2 x 2 m grid). Rural areas were surveyed using one point per maximum of 25 m^2 with 0.5 m vertical accuracy, producing 1 m interval contour lines, from which was derived a regular grid DEM with one point per 4 m^2 (2 x 2 m grid). For the single region-wide DEM, the resolution of urban areas was coarsened to match that of the rural areas. This was the final form of the DEM provided by Auckland Regional Council. To estimate the threshold contributing area we used the catchments surveyed by Wilding and Parkyn (2006). A separate threshold contributing area was calculated from Wilding and Parkyn (2006) for permanent, intermittent and ephemeral streams. In this approach, we assumed that:

1. The Auckland 2 m DEM was as accurate as specified in the DEM metadata. We did not test or evaluate this.
2. Intermittent streams always occur upstream of permanent, and ephemeral streams always occur upstream of intermittent. The data of Wilding and Parkyn (2006) showed that this is not always the case. However, Auckland Regional Council's (in prep.) definition of intermittent streams includes all stream reaches downstream of an intermittent reach and for permanent streams includes all reaches downstream of a permanent reach. We used that definition to classify stream reaches as ephemeral, intermittent or permanent in the data set of Wilding and Parkyn (2006).

3.3 Calculating threshold contributing area from test catchments

Of the 32 catchments surveyed by Wilding and Parkyn (2006), we used 26 that were fully within the Auckland Region boundaries and contained suitable data. These 26 catchments were distributed among four hydrogeological areas (HGAs; Wilding and Parkyn 2006).

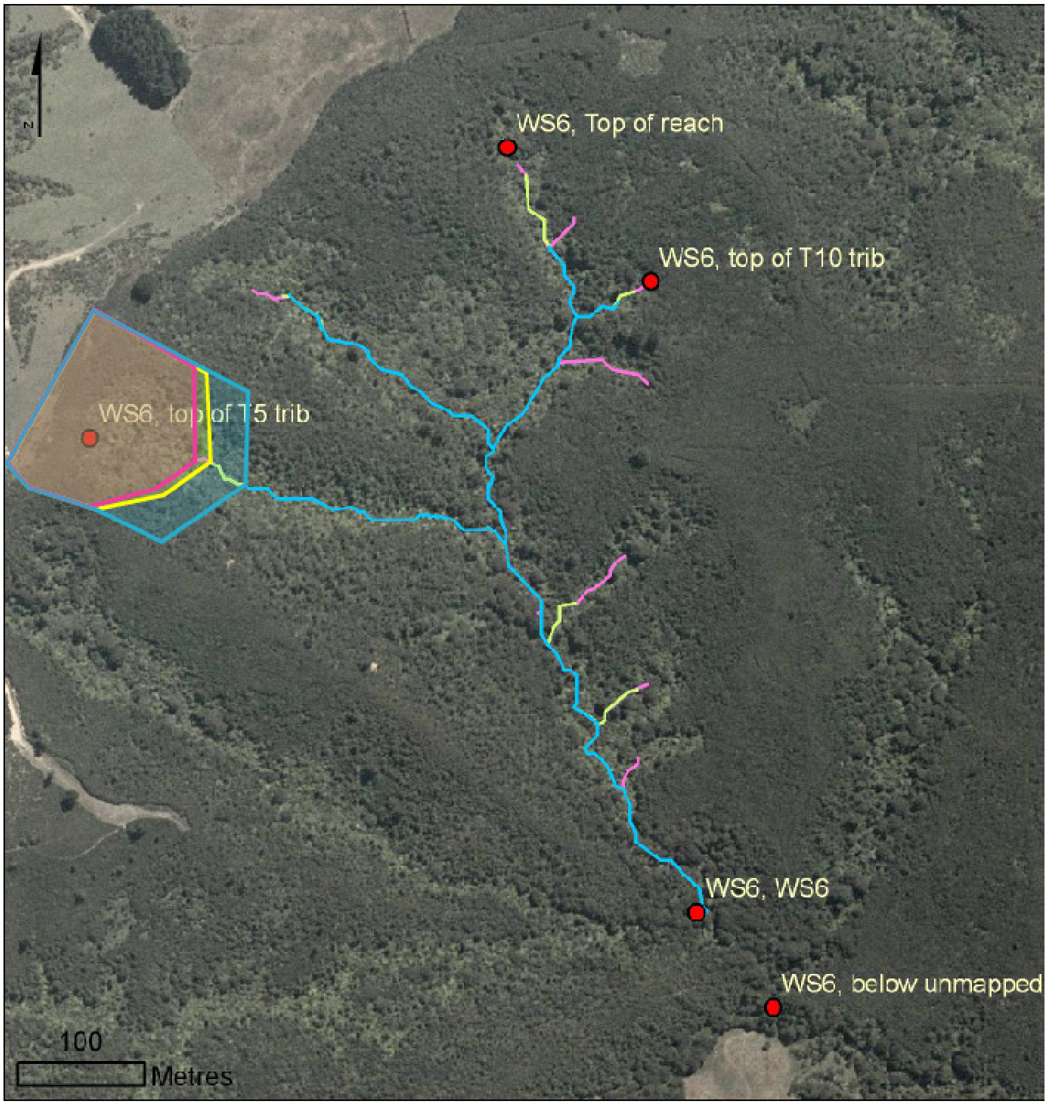
In each catchment, the total lengths of permanent, intermittent and ephemeral tributaries recorded by Wilding and Parkyn (2006) were calculated, using ARC's (2008) definitions (above) and the methdology described in Storey *et al*. (2008). Then for each catchment, the Hydrology Tools sequence was run repeatedly with a range of threshold contributing area values (see Figure 2), and in each run the total length of the resulting digital stream network was recorded. The digital stream lengths closest to the observed lengths for permanent, intermittent and ephemeral streams were noted and the threshold contributing area values that produced these lengths were recorded.

Among the 26 test catchments, the resulting contributing area thresholds were highly variable, and included a number of outliers and extreme values. This variability is likely due to a number of factors that differed between catchments, including hydrogeological area (HGA), land use, rainfall, surface soil type, catchment slope and presence of artificial drainage structures such as mole/tile drains. The influence of the first three of these factors was estimated using linear regression in SPSS (v 11) statistical software. Land use data were derived from the New Zealand Land Cover Database (LCDB2) and rainfall data were derived from the Land Environments of New Zealand (LENZ) climate layers (Leathwick et al. 2003). Because HGA had the strongest influence and was the only factor that could easily be incorporated into the analysis, the test catchments were grouped only by HGA.

Grouping the test catchments by HGA greatly reduced the variability in threshold contributing area, however some outliers and extreme values remained. These values strongly skewed the estimates of average contributing area calculated for each HGA. We did not have catchment-specific information that would give us reason to exclude these outliers from the analysis, therefore we needed to incorporate those values without allowing them to unduly influence the average. The best method to incorporate them was, for each stream type, to sum the total length of all stream reaches in each HGA, and compare the digital stream lengths to the surveyed stream lengths by HGA instead of by catchment to obtain threshold contributing area values. The result was an estimate of threshold contributing area for each of the three stream types and each of the four HGAs. Further, for each combination a lower and upper threshold was determined from the samples. These 36 values (Tables 1-3) were used as the input data for channel mapping across the whole Auckland Region.

Figure 2:

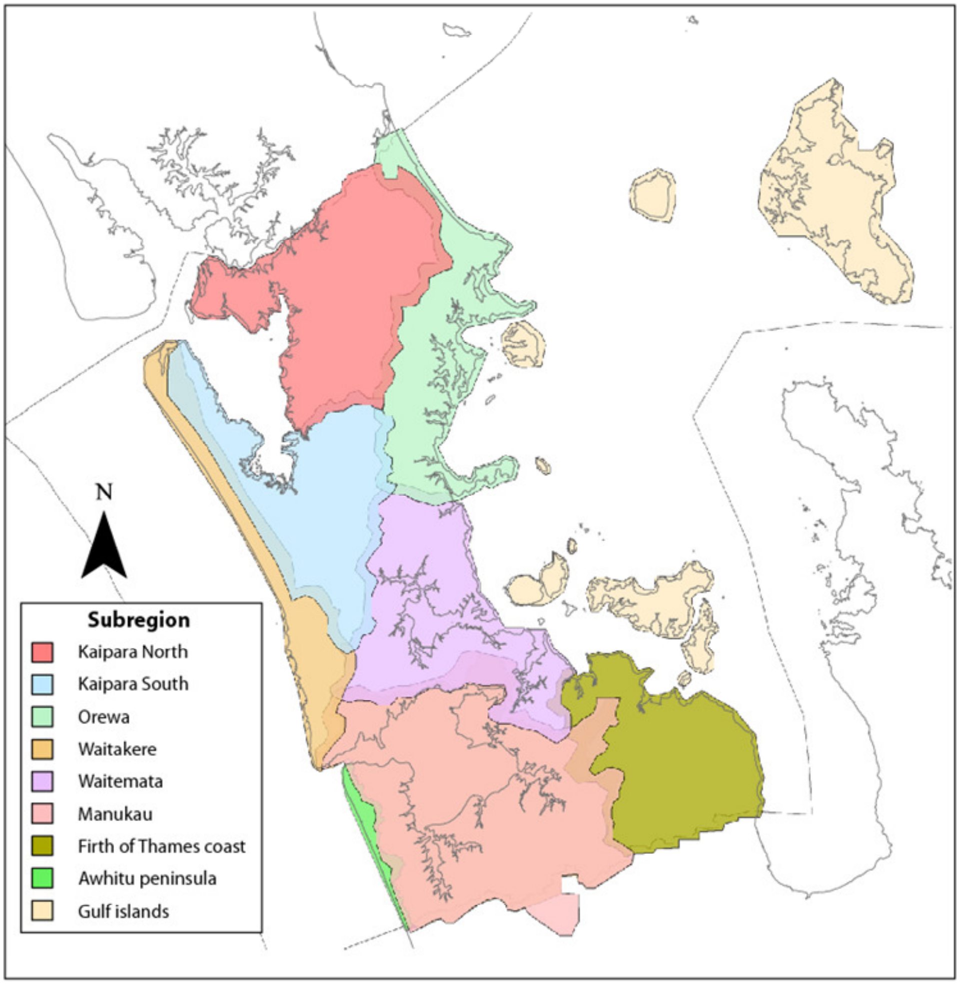
Example test catchment showing three runs of the Hydrology Tools using different threshold contributing areas: low (0.92 ha; pink) producing the greatest total stream length; intermediate (1.32 ha; yellow) producing a medium total stream length; and high (2.2 ha; blue) producing the shortest total stream length. Red dots show the actual channel heads recorded by global positioning systems (GPS) in the field survey. The shaded areas show the threshold contributing area for each run. Threshold contributing area relates to the catchment area above the channel head – the point in the catchment where a stream channel is initiated.



3.4 Extrapolating test catchment results to the whole Auckland region

Processing an area of 500 000 hectares at 2 m resolution was beyond the capacity of the available computers. Therefore the first step in the region-wide analysis was to divide the Auckland Region into 9 sub-regions by major catchment (e.g., Manukau Harbour catchment, Waitemata Harbour catchment,etc.; see Figure 3). The analysis was run separately in each of these sub-regions, and the final results summed to produce the region-wide statistics.

Figure 3:
Auckland Region, divided into 9 subregions to reduce the computer processing power needed at each step of the digital terrain analysis.

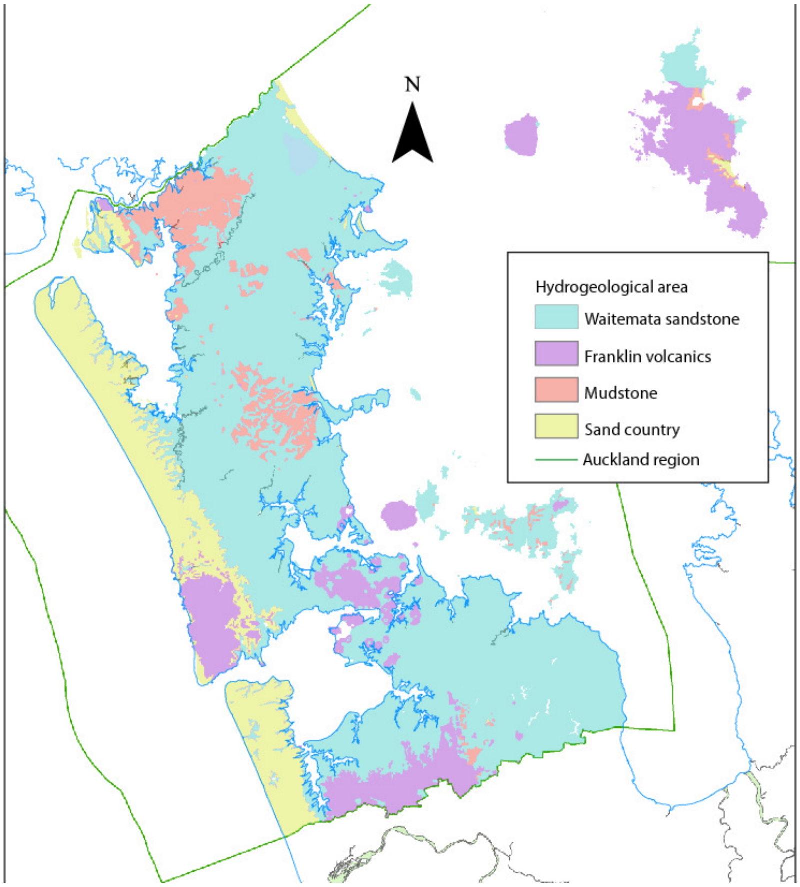


To account for the influence of underlying geology, the region was also divided into four different HGAs. These were Waitemata Sandstone, Franklin Volcanics, Mudstone and Sand country (see Figure 3). It is acknowledged that there are more than four HGAs present in the Auckland Region. In particular there is the andesite/breccia group underlying much of the Waitakere Ranges, greywacke underlying the Hunua Ranges and Waiheke Island, and limestone underlying northern areas around Wellsford. Although these are likely to show different hydrological characteristics, time and budget did not allow additional field work to obtain stream length data from these HGAs. Therefore HGAs without data were grouped with others that had data, according to best knowledge of their hydrology (A. Smaill, ARC, pers. comm.) Andesite/breccia was grouped with Franklin volcanics, greywacke was grouped with Waitemata sandstone, and limestone was grouped with mudstone. In each of the four HGAs, a different threshold contributing area was used.

The Hydrology Tools sequence was run separately for each of the three stream types using the suite of threshold contributing areas appropriate for each type. Stream reaches that were duplicated in the overlap of the boundaries between sub-regions were removed by assigning them a value of 1 in an attribute field called "Other catchment", then selecting only reaches with a zero value in this field for the stream length calculations. In urban areas, many streams are piped and therefore do not actually exist as open channels. We removed these stream reaches using a conservative approach that would more likely underestimate than overestimate total stream length in urban areas. Stream reaches occurring within 30 m of a stormwater pipe (as shown by GIS "underground services" layers provided by the seven territorial authorities in the region) were removed. Due to the density of the stormwater network in most settlements, this criterion removed almost all streams in urban areas. Some urban streams are, of course, unpiped. We assumed that all unpiped urban streams are higher-order permanent streams that appear in the 1:50 000 topographic map. Therefore after removing urban streams from the digital stream network by the above procedure, we added the total length of topographic map streams in urban areas to the final estimate of permanent stream length.

The final step for each stream type was to sum the lengths of all stream reaches from the 9 sub-regions.

Figure 3:
Hydrogeological areas for Auckland Region used in stream channel mapping.



3.5 Calculating confidence limits:

To calculate 95% confidence limits on values of stream length, the Hydrology Tools sequence was run twice more for each stream type, using upper and lower 95% confidence limits of threshold contributing area from the 26 test catchments. These confidence limits were calculated using a non-parametric statistic rather than a parametric one, so that the influence of outlying and extreme values did not skew the estimates. In three of the four HGAs there were only 5-6 test catchments. Because the sample size was so small, the 95% confidence limits in these HGAs corresponded to the smallest and largest estimates of contributing area. These values were used except where they represented an outlier or extreme value (outliers were defined as values 1.5-3 times greater or less than the interquartile range; extremes were defined as values more than 3 times greater or less than the interquartile range). In those three cases, the next closest estimate of threshold contributing area was used.

3.6 Classifying stream lengths by stream order

Stream order was calculated using a separate tool called “Stream order” in the ArcGIS Hydrology Tools toolbox. This tool assigns a Strahler stream order to each stream reach, using the output from Stream Link as source data. This analysis was performed on the permanent stream network.

4 Results and discussion

4.1 Threshold contributing areas for test catchments

After running the Hydrology Tools repeatedly in the test catchments with different values of threshold contributing area, a relationship between threshold contributing area and total length of the stream network was obtained for each HGA (Figure 4). From these relationships, a threshold contributing area that matched the total stream length in the test catchments was obtained (Tables 1-3).

Figure 4:
Relationship between total stream length and threshold contributing area in test catchments, grouped by hydrogeological area.

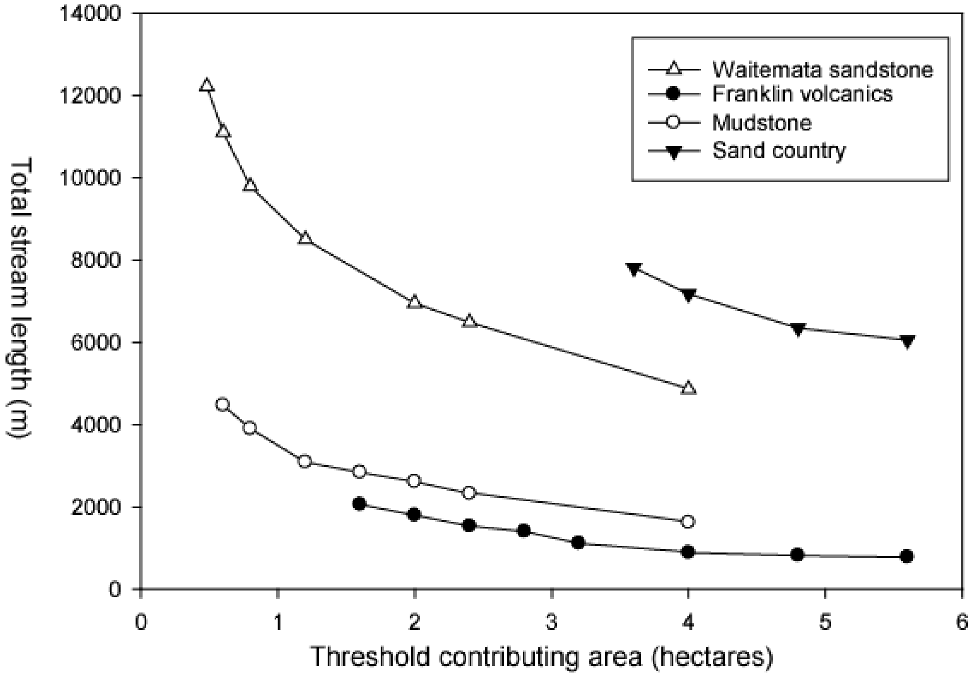


Table 1:

Threshold contributing areas (i.e., the size of catchments where stream channels are initiated) used for calculating best estimate of total stream length in Auckland Region. All values are in hectares.

	Permanent	Permanent + Intermittent	Permanent + Intermittent + Ephemeral
Waitemata sandstone	2.8	1.68	0.84
Franklin volcanics	4.4	2.08	1.52
Mudstone	3.2	1.6	0.64
Sand country	5.8	5.44	3.88

Table 2:

Threshold contributing areas (i.e., the size of catchments where stream channels are initiated) used for calculating upper 95% confidence limit for total stream length in Auckland Region. All values are in hectares.

	Permanent	Permanent + Intermittent	Permanent + Intermittent + Ephemeral
Waitemata sandstone	2.2	1	0.6
Franklin volcanics	2.6	0.48	0.4
Mudstone	1	0.32	0.32
Sand country	3.4	1.6	1

Table 3:

Threshold contributing areas (i.e., the size of catchments where stream channels are initiated) used for calculating lower 95% confidence limit for total stream length in Auckland Region. All values are in hectares.

	Permanent	Permanent + Intermittent	Permanent + Intermittent + Ephemeral
Waitemata sandstone	3.8	2.4	0.92
Franklin volcanics	9.6	4.8	3.4
Mudstone	3.2	2.2	1.48
Sand country	9.6	9.6	4.2

4.2 Influence of HGA, land use and rainfall on threshold contributing areas

The influence of three factors – hydrogeological area (HGA), land use and rainfall – in explaining the variability in threhold contributing area between test catchments is described by multiple regression statistics in Table 4. Of the three factors, only HGA consistently had a statistically significant effect on threshold contributing area. The different hydrological characteristics in each HGA result from the different water storing and transmitting properties of the different underlying rock types.

Table 4:

Multiple linear regression of hydrogeological area (HGA), land use and rainfall vs the threshold contributing area for permanent, intermittent and ephemeral streams. R^2 refers to the proportion of variability in threshold contributing area that is explained by the combination of the three factors. The statistics for HGA, land use and rainfall relate to the separate effect of each factor on contributing area. Beta is the standardised regression coefficient. n.s. means not significant at the 0.05 significance level.

	Permanent	Intermittent	Ephemeral
R^2	0.136	0.196	0.320
ANOVA	F=2.263; df=3,43; p=0.095 (n.s.)	F=4.377; df=3,54; p=0.008**	F=12.088; df=3,77; p<0.001***
HGA	Beta=0.210; p=0.221 (n.s.)	Beta=0.402; p=0.007**	Beta=0.616; p<0.001***
Land use	Beta=0.200; p=0.186 (n.s.)	Beta=0.181; p=0.157 (n.s.)	Beta=0.123; p=0.199 (n.s.)
Rainfall	Beta=-0.086; p=0.597 (n.s.)	Beta=0.117; p=0.403 (n.s.)	Beta=0.227; p=0.037*

4.3 Stream lengths

The total length of permanent, intermittent and ephemeral streams for Auckland Region, obtained using the above values of threshold contributing area, are shown in Tables 5 and 6. Note that the lower and upper confidence limits are not symmetrical about the best estimate, because the slope of stream length vs threshold contributing area gets steeper at low values of threshold contributing area (Figure 4).

Table 5:

Net lengths of permanent, intermittent and ephemeral streams in Auckland Region, in km.

	Permanent	Intermittent	Ephemeral
Best estimate	16650	4480	7110

Table 6:

Lengths of permanent, permanent+intermittent and permanent+intermittent+ephemeral streams in Auckland Region, with upper and lower 95% confidence limits. Confidence limits mean that there is a 95% probability that the true stream length lies between the lower and the upper values given below. All values are in km.

	Permanent	Permanent + Intermittent	Permanent + Intermittent + Ephemeral
Best estimate	16650	21130	28240
lower 95% confidence limit	14110 (-15%)	17340 (-18%)	25520 (-10%)
upper 95% confidence limit	20190 (+21%)	31620 (+50%)	37820 (+34%)

Lengths of permanent streams classified by Strahler stream order, are shown in Table 7. In the upper confidence limit scenario, the extra stream length is of course added at the top of the stream network, i.e., this scenario adds first order streams to the network. However, when first-order streams are added to the stream network, streams designated as first-order in the "best estimate" scenario become second-order, those designated as second-order become third-order, etc. Therefore, the total length values change not just for first-order streams, but all stream orders. The same effect occurs in reverse for the lower confidence limit scenario.

Table 7:

Length of permanent streams in Auckland Region, classified by stream order. Values are in km.

Stream order	Total length	Total length (lower 95% confidence limit)	Total length (upper 95%confidence limit)
1	8753	7459	10558
2	4262	3588	5156
3	2121	1847	2533
4	1003	826	1218
5	372	266	504
6	122	106	133
7	16	17	88
Total	**16650**	**14110**	**20190**

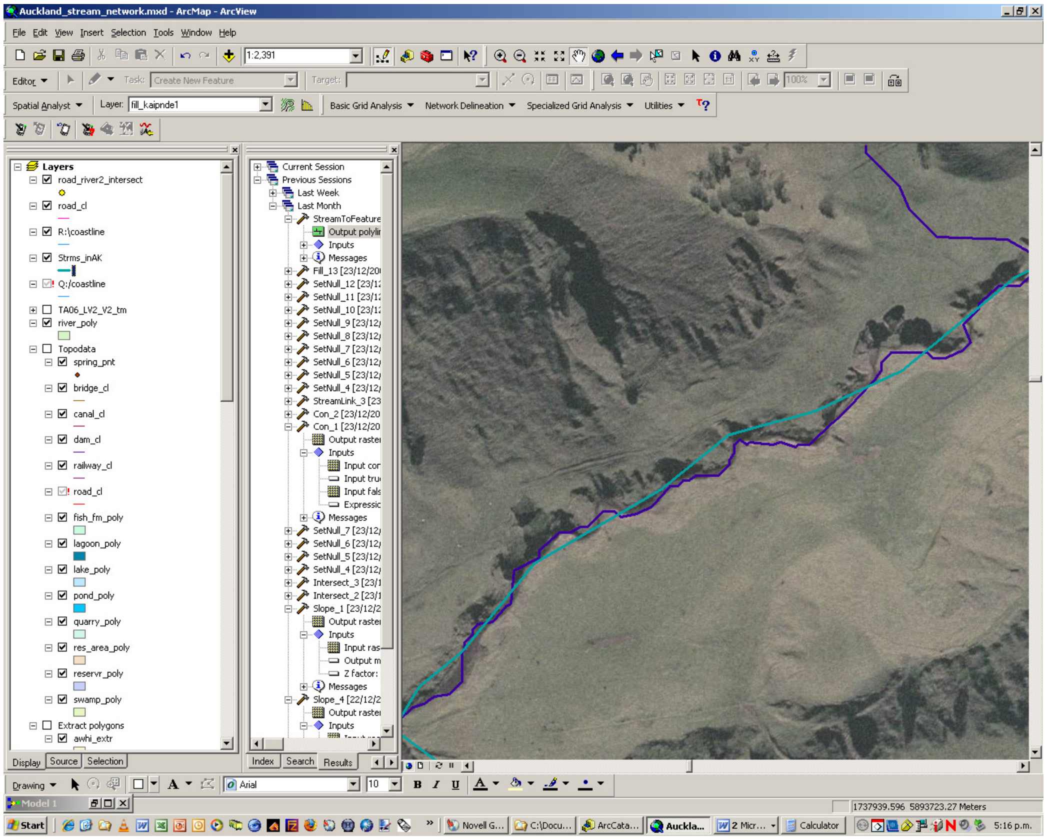
4.4 Relationship between the digital stream network and topographic map blue lines

The total length of permanent streams derived from our digital stream network is 77% higher than the 9427 km of "blue line" streams shown in 1:50 000 topographic maps of the Auckland Region. Even the lower estimate is 50% higher, and the upper estimate is 114% higher than the blue line length. There are two main reasons for this. First, according to a technical specification the topographic maps do not show tributaries less than 500 m long (National Topographic/Hydrographic Authority 2003), whereas the digital stream network shows all tributaries regardless of length. Our analysis showed there are over 6000 km of first-order permanent streams less than 500 m long. This figure would be even higher if we included second-order streams that also were omitted from the topographic maps because their length, combined with that of their first-order tributaries, was less than 500 m.

The second reason that our calculated length of permanent streams was greater than the topographic map blue line length is that the topographic map blue lines have undergone "cartographic simplification". This means they smooth over the fine scale meanders that occur in small streams (see Figure 5). A comparison of ten randomly selected stream reaches across the region, each 700-1300 m long, showed that topographic map blue lines were 4-17% shorter than the corresponding reach in our digital stream network, because of this smoothing.

Wilding and Parkyn (2006) found that in headwater areas topographic map blue lines typically extended further up the catchment than surveyed permanent reaches, therefore included reaches classed as intermittent or ephemeral. Since it was based on the data of Wilding and Parkyn (2006), the same was true for our digital stream network; topographic map blue lines often extended 50 to 200 m further up the catchment than our permanent stream network. This pattern would increase the topographic blue line length relative to the length of permanent streams in our analysis, therefore the first two effects described above must have added more than 77% to the topographic blue line length.

Figure 5:
Example of "cartographic simplification" in the topographic map blue line (light blue), and the finer scale of stream meandering in the digital stream network (dark blue) which better matches the actual stream meandering. Total stream lengths for this reach were 662m, 751 m and 789 m for topographic map blue lines, digital stream network lines and tracing the aerial photograph respectively.



4.5 Validation of model

Because field data were scarce, we used all the data available to derive the threshold contributing areas. This left no extra field data with which to validate the model, i.e., to test how well it predicted stream lengths in a new catchment. Therefore we advise always reporting the confidence limits along with the stream length values in order to provide robustness to the estimates.

4.6 Sources and magnitude of error

Several sources of uncertainty potentially reduced the accuracy of the stream length values. The greatest source of uncertainty was undoubtedly in selecting the appropriate threshold contributing areas, as these determine the point of channel initiation in each catchment, and hence the total stream length. Figure 4 shows that total stream length is very sensitive to changes in threshold contributing area, particularly at contributing areas less than 1 hectare. The main difficulty was that, in field surveys of the test catchments, the point of stream channel initiation varied greatly; for example among 42 tributaries in 6 mudstone catchments, permanent streams were initiated at contributing areas ranging from 0.3 to 7.3 hectares. A number of factors potentially contributed to this variability. Underlying geology, catchment land slope, surface soil properties, land use, rainfall and the presence of artificial drainage devices such as mole/tile drains all could influence where in the catchment stream channels are initiated, and how the point of initiation varies with season and rainfall events. Multiple regressions indicated that geology (here referred to as hydrogeological area, or HGA) was the factor most strongly influencing our test catchments. We accounted for this factor by stratifying the test catchments and the full Auckland Region analysis by HGA. However the other factors remained unaccounted for, and we had to assume that among our 26 test catchments we were able to estimate average conditions for these other factors. However, because we had as few as 5 test catchments in some HGAs, we must be cautious about the accuracy of our average threshold contributing area estimates. Our 95% confidence limits (Table 6) indicate that we may have overestimated permanent stream length by as much as 15% or underestimated it by as much as 21%.

Related to the above, we lacked field data for three main hydrogeological areas; andesite/breccia in the Waitakere Ranges, limestone in northern areas around Wellsford and greywacke in the Hunua Ranges and Waiheke Island. For these areas we used values from HGAs with the most similar hydrology. Since andesite/breccia occupied about 3% of the region, limestone less than 2% and greywacke about 12.5% of the region, only errors in values for greywacke could potentially have caused a noticeable error in our stream length estimates.

Other sources of error or uncertainty are estimated to have caused much smaller errors in our stream length estimates. A particular issue for stream channel mapping is choosing a realistic resolution for mapping stream sinuosity. In a recent study, the true length of a Waikato stream, defined by following the stream thalweg, was found to be 30% longer than length shown on a topographic map (L. Mckergow, pers. comm.) because the low resolution of the topomap resulted in smoothing of the stream meanders. When working with the test catchments, we chose to use "stream line simplification" ("Simplify polylines" in the Stream to Feature tool), as this produced stream meanders that matched the "trailing string" technique used by Wilding and Parkyn (2006) to measure the stream lengths. We used the same "simplify polylines" function in our regional scale analysis. To determine whether the resolution of our mapped stream lines matched that shown by aerial photographs, we overlaid the stream lines on aerial photographs in randomly selected catchments, and measured the length of both using the GIS "ruler" tool. We found that over 10 randomly-selected reaches, each 700-1300 m long, our mapped streams underestimated the stream length visible from the aerial photos by an average of 2%.

The remaining errors were largely due to the difficulties of mapping stream channels in flat landscapes. On naturally flat areas, the Hydrology Tools sometimes mapped straight channels traversing directly across the flat area whereas aerial photos showed a meandering channel. In these cases the mapped channels underestimated the true stream length. On other flat areas aerial photos showed straight drainage ditches whereas the Hydrology Tools produced a meandering channel. In these cases, the mapped channels overestimated the true channel length by up to 10%. Occasionally the Hydrology Tools produced two stream channels across flat areas where in fact there was only one. In these cases the true stream length was overestimated by up to 100%. Some flat areas were produced by the Hydrology Tool sequence itself. An artefact caused by the "Fill" procedure in the Hydrology Tools was that the flow paths beneath culverts and bridges were not recognised, and these features were therefore interpreted as barriers to flow. Therefore, the areas behind them were filled as if water were being impounded. The filled areas were modelled exactly flat, and the stream channels created by later steps in the mapping procedure were straight lines rather than meandering channels.

Areas with slope less than 0.1° (including true flat areas and areas made flat by the Fill process) represented 5% of the whole Auckland Region. However, only some flat areas had errors associated with them. Furthermore, some of the errors associated with flat areas overestimated and some underestimated true stream length, therefore the effects of these errors cancelled each other to some extent. For these reasons, errors associated with flat areas are believed to have minimal effect on total estimates of stream length.

4.7 Using the digital stream network to locate streams

Since the stream network was intended primarily to estimate the total length of permanent, intermittent and ephemeral streams in Auckland Region, it was not designed to show the exact locations of these three stream types in the landscape. Therefore a great deal of caution must be exercised if the stream network is used to locate specific stream reaches. In test catchments, the digital stream network produced some first-order tributaries that were not found in field surveys and omitted some that were found. This discrepancy occurred only among first-order tributaries, therefore the channel heads of permanent streams, and the start and end points of intermittent and ephemeral streams, must not be interpreted too closely. The input values for channel mapping were optimised to match the overall stream length of the test catchments, but not necessarily the correct locations.

Some other errors in the channel mapping also were not corrected because they would not significantly affect total stream length of the region. The location of stream channels across very flat land or within a hundred metres upstream of culverts and bridges, and the presence or absence of streams in the vicinity of stormwater pipes also should not be regarded as accurate. No attempt was made to account for the effects of mole/tile drains on streams in individual catchments.

Despite these cautions, the same process used here to derive a digital stream network for Auckland Region could be used to produce an accurate map of stream channel locations. This would require correcting small-scale artefacts in the channel mapping process and further ground-truthing of the channel map.

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