Traditional, definition of such areas has been performed manually, taking into consideration the topography of a region and smaller features, such as irrigation channels, roads and other man-made features. This method, although perhaps the most reliable, is tedious and time-consuming, especially for large catchments. In the 1960s, with the advent of computer technology, researchers began to see the potential of digital technology to perform this task automatically by computers. Since that time, there have been a great number of research activities into various algorithms that could delineate a catchment. Major progress was achieved in the 1980s and some methods have been incorporated into modern GIS packages such as ArcView.

Currently, there are many digital data types available and it is a tricky task to choose suitable data for catchment delineation purposes. Researchers and practitioners frequently have access to digital elevation models (DEMs). These can be classified into three groups:

(a) two-dimensional arrays of numbers representing the vertical elevation (above some datum), known as raster grids or grid DEMs. In this study, all DEM data are in this category.

(b) a list of x, y, and z coordinates, for an irregular network, known as a triangulated irregular network (TIN)

(c) vector data in the form of contour strings that link points of equal elevation: these data types are exchangeable and, in practice, a DEM is commonly used in computer catchment boundary delineations.

The DEM data used in this study were obtained from Digitimap, an EDINA service (data library service at the University of Edinburgh) delivering Ordnance Survey map data to higher education in the UK. The data were derived from two Ordnance Survey Landplan® data products, each available in two forms, vector (contour) and DEM data. The first product is Land-Form PROFILE™ data at a 1 : 10 000 scale. The contour data were produced from Ordnance Survey 1 : 10 000 scale mapping, which was recontoured as part of a programme, completed in 1987, using photogrammetric techniques and recorded to the nearest 1.0 m. Some small areas, which were not visible on the photography, were surveyed by ground methods. The DEM data on a 10 m grid scale were then mathematically derived from the contour data. The second product is Land-Form PANORAMA™ data produced at a 1 : 50 000 scale. Again, the contour data were produced first and the DEM derived from these.

It has been noted that researchers are often unaware of the limitations of digital elevation models and any resulting automated processing that follows from this. Martz and Garbrecht discussed some of the errors that are inherent in DEM data, arising from overestimation or underestimation of point heights, resulting in errors in flow routing. Thieken et al. discuss the effect of DEM resolution on a fixed catchment area. The aim of this paper is to provide the readers with some guidelines on how to use DEMs to delineate catchments, pointing to...
out their strengths and weaknesses, based on a case study for the
Brue catchment in the south-west of England. This work is
primarily aimed at practising engineers, but the lessons will
hopefully also be valuable for researchers.

2. STUDY AREA
The area chosen for this study is the Brue catchment in Somerset,
in the south-west of England. It was the site of the Natural
Environment Research Council (NERC)-funded HYREX project
(hydrological radar experiment) from 1993 to 1997. The site has a
catchment area of approximately 135 km\(^2\), with its outlet at
Lovington, where a gauging station is placed. The catchment is
mainly on clay soils, predominantly rural and of modest relief,
with spring-fed headwaters rising in the Mendip Hills and
Salisbury Plain. Clays, sands and oolites give rise to a rapidly
responsive flow regime. The average annual rainfall from 1961 to
1990 was 867 mm. From 1917 to 1955, the town of Bruton,
within the catchment, held the national record for the highest
one-day rainfall total at 243 mm. The catchment was chosen for
the HYREX project, as its size and relief of the catchment were
seen as representative of many catchments in the UK requiring
flood warning using rainfall–runoff modelling methods.
During the HYREX project, the site was covered by 49 rain
gauges. The site is therefore a data-rich environment. A DEM of
the site is shown in Fig. 1.

3. COMPARISON OF BOUNDARIES FROM DIFFERENT
METHODS
3.1. Delineation methods
The Brue catchment is delineated by six methods in this study
(a) manual delineation
(b) automatic delineation using 10 m raster DEM data
(c) automatic delineation using 50 m raster DEM data
(d) automatic delineation using 1 : 10 000 vector contour data
(e) automatic delineation using 1 : 50 000 vector contour data
(f) the existing boundary used by the Environment Agency.

Manual delineation is the traditional method of delineating the
drainage basin and should yield the best quality if sufficient time
and high-quality maps are available. The delineation needs to be
performed carefully and can take account of not just the
topography but man-made features, such as irrigation canals,
roads and railway tracks. It is worth noting that because of the
interaction of surface runoff and sub-surface flows, there may be
a discrepancy between the topographic divide and the phreatic
divide (or groundwater divide). In this work, the assumption is
made that the drainage basin can be delineated along the
topographic divide. The delineation was performed with a
combination of Ordnance Survey raster data at a 1 : 10 000 scale
(as a background), derived from Ordnance Survey Landplan®
products, and with 1 : 10 000 contour data, derived from Land-
Form PROFILE™ data. The tracing of the catchment boundary
was carried out in an ArcView environment by hand. In addition,
the existing catchment boundary map used by the Environment
Agency was used in this study, which was used throughout the
HYREX project and cited by Wood et al.\(^8\)

Automatic delineation methods have been incorporated into
hydrological analysis software by numerous researchers. This
study uses the HEC–GeoHMS software, which is the most popular
package among practising engineers and freely available from
the US Army Corp of Engineers.\(^9\) The fundamental concept in
automatic delineation is that calculations of the flow direction
are based on topography. The method incorporated into the
software is widely described in the literature as the ‘D8 method’
and is best described by Jenson and Dominique.\(^10\) It begins with
the assumption of a grid cell surrounded by eight cells as shown
in Fig. 2. The algorithm assumes that the distances to adjacent
cells on the ordinal directions have a unit length, whereas the
distances to the corner cells have a distance $\sqrt{2}$ times the unit
length. It is worth highlighting that the cell in the direction of the
steepest downward slope is not always the cell with the greatest
elevation difference. Cells are then assigned integers representing
the eight possible flow directions, and these integers are stored
in an array. The direction integers are shown in Fig. 3. Other
methods to determine the flow direction have been developed
and tested and are well referenced by Costa-Cabral and Burges.\(^11\)
They include multiple directional flow algorithms and algorithms
with stochastic components.

From this starting-point, the modeller is confronted by a number
of problems. The most important of these is to deal with pits (or
sinks), followed by the determination of flow direction in flat
areas. Pits are depressions in DEM data, where all the surrounding
cells have a higher elevation. The modeller has to decide whether
these pits are remnants from the digitising process—spurious

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<table>
<thead>
<tr>
<th>Single flow direction in</th>
<th>steepest downslope direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 20 20</td>
<td></td>
</tr>
<tr>
<td>18 19 18</td>
<td></td>
</tr>
<tr>
<td>18 17 18</td>
<td></td>
</tr>
</tbody>
</table>

---

Fig. 1. DEM of the region

Fig. 2. D8 flow algorithm
pits—or whether they are representative of physical features in
the topography. Most researchers assume the former, although it
is worth highlighting that this is not universally the case. The
most common method is to ‘fill’ the depression by raising each
cell’s elevation to the elevation of its neighbour of lowest
elevation, if that neighbour is higher in elevation than the cell.
Flat areas are commonly treated in an iterative fashion from
some assumed outlet.

The automatic delineation was performed using several data product
sources. First, 10 m DEM data were extracted from Land-Form
PROFILE™ data, which were downloaded as raster DEM data. These
data were also available as vector contour data. These were
converted into TIN data and used to delineate the catchment. Then
50 m Land-form PANORAMA™ data were downloaded both as
raster data and as 1 : 50 000 vector contour data. Thus, the watershed
was delineated automatically from four different data sources.

3.2. Comparison of results

The results are summarised in Table 1. The method assumes that
one ‘true’ catchment exists and this is the catchment delineated
manually (Fig. 4). The overestimated area is the area enclosed
within the catchment boundary being assessed, that lies outside
the catchment boundary used as the standard. The
underestimated area is the area enclosed within the catchment
boundary used as the standard that is not enclosed within the
catchment that is being assessed. To clarify this, set notation can
be used. If \( A \) is the catchment boundary that is to be assessed and
\( B \) is the catchment boundary used as the standard, then the
overestimated area can be stated as \( A - A \cap B \), whereas the
underestimated area can be stated as \( B - A \cap B \), where \( A \cap B \) is
the intersection of the two areas. These two areas can be summed
to give the total error, which is analogous to the mean absolute
error. This approach allows one to distinguish between two
catchment boundaries that enclose equal areas that have different
shapes and positions.

For most of the boundaries (Figs 5–9) there is good agreement
with the manually delineated catchment (Fig. 4). There appear to
be three areas of disagreement and a little further investigation
should elucidate the problems. The first is towards the western
segment of the catchment. This problem appears to be due to a
roadway that intersects a stream channel along that portion of
the boundary. The stream is redirected away from the catchment,
causing a subcatchment to be placed outside the catchment. This
highlights the need for care when dealing with man-made
features within catchments. The second problem area appears to
be in the north-western segment of the boundary, near the Royal
Bath and West showground. Here, a number of drains have been
constructed around the perimeter of a large site. The site is also
noticeably flat, and it is difficult for an automatic method to pick
up on the true stream network. Finally, the third problem area is
towards the northern segment of the catchment boundary.
Towards the eastern side of this problem area there is a quarry,
and it appears that a stream flows underground to appear on the
other side of the catchment boundary. It is difficult to tell where
the water would naturally flow, but it is possible that, again, a
man-made feature has altered

The conclusion that one can draw
from this first part of the work
is that all the automatic
methods tested using

<table>
<thead>
<tr>
<th>Delineation method</th>
<th>Total area: km²</th>
<th>Overestimate: km²</th>
<th>Underestimate: km²</th>
<th>Total error: km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>136.15</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Automatic—10 m DEM</td>
<td>150.47</td>
<td>17.00</td>
<td>2.68</td>
<td>19.68</td>
</tr>
<tr>
<td>Automatic—50 m DEM</td>
<td>144.01</td>
<td>9.80</td>
<td>1.83</td>
<td>11.63</td>
</tr>
<tr>
<td>Automatic contour—1 : 10 000</td>
<td>166.33</td>
<td>29.89</td>
<td>2.78</td>
<td>32.67</td>
</tr>
<tr>
<td>Automatic contour—1 : 50 000</td>
<td>142.41</td>
<td>12.35</td>
<td>6.10</td>
<td>18.45</td>
</tr>
<tr>
<td>EA border</td>
<td>142.38</td>
<td>8.33</td>
<td>2.11</td>
<td>10.44</td>
</tr>
</tbody>
</table>

Table 1. Summary of catchment delineation results
commonly available software produce errors. This begs the question whether any automatic method is capable of perfectly representing a catchment boundary as accurately as the manual method carried out by experienced personnel.

4. VARIATIONS OF COMPUTED BOUNDARIES Owing TO DEM Resolution

4.1. DEM with different resolutions

Clearly, data resolution may be expected to influence the computer-generated boundary results. It would be very useful to analyse the variations of boundaries owing to the DEM scale. In order to investigate this, the 10 m DEM data were selected and the grid resolution increased (by interpolation) to 20, 30, 40, 50, 100, 150, 200 and 500 m resolution. This was performed using two methods. The first was simply to select the nearest cell when reducing the resolution and the second was to use a method known as bilinear interpolation. This is a method commonly used in image processing to change the size of an image. With this method, the problem of aliasing can arise. Aliasing occurs when the pixel resolution is too coarse to pick up steep changes in pixel values. To eliminate this problem, a low pass filter is applied to the data—that is, simply taking the arithmetic average of the cell and the eight cells surrounding it. This has a smoothing effect on the data. Bilinear interpolation can then be applied. A bilinear filter is a mathematical method for interpolating a new cell’s value within a $2 \times 2$ neighbourhood of cells. It is a suitable method for both increasing and reducing the resolution of an image.

In this study, the boundary produced from the 10 m DEM grid is used as a benchmark to compare the boundaries produced by other map resolutions. Since the purpose of this part of the study is to explore the variations in computer-generated catchment boundary, a manually produced boundary is not included in this analysis. For each boundary map, it is possible to measure the total overestimated and underestimated areas in relation to the benchmark catchment area, and thus calculate the total error, as described in section 3.2. The second type of statistic is to calculate the flow length from each point in the catchment to the outlet at Lovington. In doing so, a histogram is produced that is analogous to a unit hydrograph, as shown in Fig. 10 for the benchmark boundary. As these distributions will vary depending on the DEM scale used to calculate the flow distance, the root mean square error (RMSE) can be calculated.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (D_{bi} - D_{ci})^2}{n}}$$

where $D_{bi}$ represents the ordinates of the benchmark distance histogram and $D_{ci}$ are the ordinates of the distance histogram for other grid resolutions. This is a good metric of the total error produced when automatic delineation is carried out at different scales. The results for the two methods of interpolation are presented in Figs 11 and 12. As the results show, there is a general increase in errors resulting from the automatic method, as the cell size increases. These increases are not perfectly regular. Note how the errors resulting from the 100 m grid vary, depending on the size of interpolation method. It is worth noticing that the apparently large error in the 100 m grid catchment, using the ‘nearest cell’ method, does not in fact translate to a proportionally large error in the RMSE. This is owing to a large overestimate of the error that occurs near the catchment outlet and does not therefore add much to the total flow length. It is a point of debate whether such a large error occurring near the
outlet is more important than an equally large error occurring further from the catchment outlet. It is also debatable whether overestimation is better or worse than underestimation and this may depend upon the perspective of the engineer.

4.2. Discussion

It is possible to assume that there are two sources of error in the catchment delineation methods as the cell size increases. The first is associated with the conversion of a vector feature (such as a line) to a raster feature. The second is that changing the grid cell size alters the topography so that a different boundary would be calculated. It is worth assessing whether the errors produced in section 4.1 are owing to the former or the latter. In order to make such an assessment, it is necessary to consider the magnitude of errors that can be expected from vector to raster (or fine raster to coarse raster) conversion. If a general shape and a general grid are chosen, it is necessary to look at the problem from a statistical point of view. Assuming there is a ‘true’ boundary line, it is possible to estimate the error that can be expected as the line is converted to a raster format. A good review of the techniques is provided by Zhang and Goodchild.\(^{12}\) One of the earliest estimates of this was made by Frolov and Maling,\(^{13}\) stating that the mean square area of the cut-off portion of each bisected boundary cell, \(V_i\) (also known as the error variance) can be estimated by

\[
V_i = aS^4
\]

where \(V_i\) is the error variance for the \(i\)th cell, \(a\) is a constant and \(S\) is the length of each grid-cell side (e.g. 10, 20, . . . , 50 m). The constant \(a\) is calculated assuming that a grid is bisected by a random straight line. Frolov and Maling\(^{13}\) suggested a value of \(a = 0.0452\) but further work by Goodchild\(^{14}\) suggested a value of \(a = 0.0619\). To calculate the total variance, it is then necessary to know the total number of cells, \(n\), that are bisected by the ‘true’ boundary. This leaves the standard error (the square root of the variance) as

\[
SE = \sqrt{(na)S^4}
\]

The problem of estimating the number of cells bisected by the boundary was tackled by Crapper,\(^{15}\) in which the number of cells are estimated as

\[
n = \frac{2k_1\sqrt{(\pi A)}}{k_2\gamma}
\]

where \(\gamma\) is a constant equal to the root mean square length of a random straight line drawn across a unit square, which was calculated as 0.794 by Goodchild. \(k_1\) is a function of the area \(A\) enclosed by the boundary and the perimeter \(L\) as shown in equation (5).

\[
k_1 = \frac{L}{2\sqrt{(\pi A)}}
\]

\(k_2\) is defined as the ‘within cell’ contortion factor. Crapper suggests that for most cases, it is reasonable to take \(k_2\) as 1. Combining these elements, it is possible to estimate the standard error as follows

\[
SE = \sqrt{\left(\frac{a}{2}\right)S^{3/2}}
\]

This last step depends on the contribution from each cell being independent. The coefficient \(a\) is calculated on the assumption

\[
\begin{array}{|c|c|}
\hline
\text{DEM grid scale: m} & \text{Standard error: km}^2 \\
\hline
20 & 0.008 \\
30 & 0.015 \\
40 & 0.023 \\
50 & 0.032 \\
75 & 0.058 \\
100 & 0.089 \\
150 & 0.164 \\
200 & 0.252 \\
500 & 0.998 \\
\hline
\end{array}
\]
that each cell is intersected by a straight line which is incompatible with independence. Applying equation (5) to the ‘true’ catchment delineated from a 10 m DEM, a shape factor of $k = 2.35$ is obtained. Applying equation (6) to these data, standard errors are produced for this problem, as shown in Table 2. These errors are significantly smaller than those obtained in section 4.1, suggesting that there is an extra source of error other than those arising from rasterisation.

However, a slightly different analysis comes from the work of Perkal$^{16}$ and the concept of an epsilon error band around a digitised line. Certainly, if one looks at Fig. 13, it is difficult to see that much of the error is from more than digitisation. The figure shows the catchment boundary derived from the 10 m DEM and from a 150 m DEM. A buffer of 150 m has been placed around the original 10 m DEM boundary, designating the maximum possible error owing to rasterisation. Although the 150 m boundary does on occasion leave the buffer zone, it can be seen that this grid is in fact a reasonable representation of the catchment.

This brings the discussion to some of the work conducted by Tarboton et al.,$^{17}$ in which the problem of choosing an appropriate grid scale was described. Tarboton pointed out that a suitable grid scale should be equal to the average slope length. This is calculated by plotting slope against the contributing area calculated by the D8 flow algorithm and identifying a point of inflection. The theory behind this is that water will flow down hillslopes along the line of steepest descent until the valley floor is reached, at which point the flow will change direction as it joins a channel, as shown in Fig. 14.

Gyasi-Agyei et al.$^{18}$ suggested that a DEM is adequate for extracting the stream network, and hence the catchment boundary, if the ratio of the average pixel drop and vertical resolution is greater than unity, as described in equation (7).

$$\frac{\text{Average pixel drop}}{\text{Vertical resolution}} \geq 1$$

where $a$ is the mean slope (m/m), $D_i$ is the grid spacing (in metres) and $\sigma_{x_i}$ is the standard deviation of the relative error. The results in Fig. 15 show that, although the ratio is greater than the grid scales, the ratio peaks between 30 and 50 m (three to five pixels, each of 10 m length), suggesting a value for the appropriate grid scale.

5. CONCLUSIONS

Computers are increasingly used in catchment delineations with digital maps. This study tackled two important issues in this area through a case study for the Brue catchment in the south-west of England. First, it has been found that no computer-generated boundaries were able to delineate robustly the catchment border. The authors believe that this is mainly because many man-made features (e.g. highways, drainage ditches, canals) can change the natural catchment boundary and the current computer algorithms could not pick up these changes. Another problem is due to the data quality, map resolution and the delineation algorithms. Therefore, manual intervention is still necessary in all catchment boundary delineations, especially in areas influenced by anthropogenic activities.

Second, the resolution of a digital elevation map can affect the delineation outcome. It is interesting to note that although the general trend of the boundary deviation increases with grid size, there is an unstable zone where this clear relationship breaks down, so it is quite likely that a finer resolution map (e.g. 10 m grid) may generate a lower-quality catchment boundary than a coarser grid (e.g. 50 m grid). To make the matter worse, it should be noted that the processing time is usually at least proportional to the squared number of cells (i.e. $O(N^2)$), so a 50 m DEM can be processed at least 25 times faster than a 10 m grid. Therefore, a
higher resolution map could not only generate larger potential errors, but also will definitely consume more computing power, in addition to the higher map cost owing to its finer resolution. The reason for this phenomenon is that the delineation error is contributed from two main sources and they dominate different parts of the resolution spectrum. In a very coarse map, the poor resolution would prevent accurate delineation owing to its rasterisation error, and the data quality (and the relevant algorithms) plays a lesser role. For a fine map, the roles of those two main error sources are swapped and the nature of the data quality error is erratic and the catchment boundary produced tends to be less robust, hence it is very important for the map user to understand this unstable zone. Further research work is needed to locate this threshold for different catchments and to provide map users with more detailed guidelines.

From this study, with the current computing technology and map data quality, it is clear that the optimum catchment boundary delineation technique should integrate both the manual method and a computer-generated method. First, a threshold grid size for the intended catchment should be chosen and a DEM near this threshold resolution acquired to generate a catchment boundary by computer. Second, a raster Ordnance Survey map with man-made features should be used (in the background) to check manually and amend the computer-generated boundary. Such a scheme is much faster than a wholly manual method and much more robust than a totally automated one.

REFERENCES


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