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Standardised Bathymetric Data Generation and Statistical Analysis of Welsh Lakes

S.D.Turner, G.L. Simpson & M.J. Hughes

CCW Contract Science Report No. 955

Report series:	CCW Contract Science Report
Report number:	955
Publication date:	February 2011
Contract number:	215 MFG 09
Contractor:	ENSIS-ECRC, University College London
Contract Manager:	Hatton-Ellis, T.
Title:	**Standardised bathymetric data generation and statistical analysis of Welsh Lakes**
Author(s):	**S.D.Turner,G.L. Simpson,M.J. Hughes**
Restrictions:	None

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Recommended citation for this volume:

Turner,S.D.,Simpson,G.L.,Hughes,M.J. 2011.**Standardised bathymetric data generation and statistical analysis of Welsh Lakes**. CCW Contract Science Report Report No: 955, [Enter number of printed pages here]pp, Publisher, Place of publication.

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EXECUTIVE SUMMARY

This report documents the methodology and procedures used to generate consistent and structured data holdings of bathymetric data from Welsh lakes. Where feasible, bathymetric data from documentary and electronic sources have been re-formatted into a consistent and accesible form and structure. We have achieved the significant task of transforming raw coordinate and depth data to bathymetric surface rasters and 0.5m interval polygon shapefiles that can be placed into GIS software. With this transformation we have generated volume/depth and area/depth data for the lakes at the same 0.5m interval. Statistical modelling of the bathymetric data shows that the collection of lakes analsyed span the spectrum of lake types found in Wales. We also show how a novel statistical approach can be used to generate bathymetric data.

1 INTRODUCTION

The shape and size of a lake basin affects nearly all physical, chemical and biological parameters of lakes (Wetzel, 2001). The surface morphology of the basin reflects the origin of the lake and current hydrological conditions. The spatial pattern and range of depths found in a lake will influence a range of physical processes – the movement of water within the lake, wind-wave mixing and sediment transport. An accurate assessment of lake water volume provides the information for determining storage and residence times of hydrological inputs. Variability in water depth and basin morphology also has a great influence on the processes operating at the sediment-water interface, e.g. determining the extent of recycling/burial of nutrients and contaminants. Biological productivity within and around a lake is greatly influenced by lake basin shape and water depth. Shallow water depths allow biologically productive littoral habitats to develop, while increased depth can provide a greater potential range of habitats.

Though the basic requirements of water depth measurements coupled to geographical locations are easily documented, the basic data is often recorded in various numeric formats and is often poorly archived (both in reports and computer databases). Many factors influence the distribution of data points in a lake, not least the method of data collection, e.g. the multitude of points gathered by an automatic logging of depth and position by a boat mounted unit compared to a handheld echo sounder with a GPS. Similarly, bathymetric data may only have been gathered non-systematically as an aside to other environmental data being recorded, e.g. plant surveys.

This report documents the process used to collate and analyse data from a variety of documentary and electronic data sources that have been used in previous CCW reports and for other research work in Wales. Because of the variety of sources and historical lack of systematic data collection protocols, the use of bathymetric data in Geographic Information Systems (GIS) has been problematic and primarily done on a site by site basis. The data supplied to CCW with this report provides a greatly improved and systematic format that allows access to existing bathymetric data, standardises structure of bathymetric data in a GIS and points the way forward for collecting, processing and archiving future bathymetric data.

2 METHODS

2.1 Collation of electronic depth and geographical location data and converting to format ready for entering into GIS.

A potential 121 sources of bathymetric data from Welsh lakes were identified for this work (Appendix 1 and in Final Data Folder_Docs/CCW Bathymetric Database_26-08_10.xls).

Four types of data were identified –

- **Type-1** Depth measurements recorded by hand-held echo-sounder and approximate geographic positions (n=29);
- **Type-2** Hand-held echo sounder measurements with Ordnance Survey grid references recorded by a hand-held GPS unit (n=21);
- **Type-3** Depth measurements obtained by a boat mounted combined GPS and echo-sounder systems operated by ENSIS-ECRC and other organisations (n=47).
- **Type-4** Maps of lakes with contour (vector) data, lacking the original point/depth data (i.e. Llyn Cwellyn in Allot et al. 1994; Jehu, 1902) which have been superseded or will require additional work, i.e. the collection of original survey data (n=15).
- **Type-0** Lake survey data known of but not forthcoming from other organisations and data holdings lost due to computer problems. This is only a small group (n=9).

For the number of Type 1 and Type 4 lakes surveyed in the past that have been superseded by later, bathymetric surveys, e.g. Gloyw Lyn, Llyn Cau, Upper Talley Lake, etc. we have used the latest, more detailed, survey data.

The list of lakes and datasets obtained for this work is shown in Appendix 1

The number of data points in some Type – 1 datasets are low. This is primarily due to when the lake was visited a detailed bathymetric survey was unachievable or not a requisite of the work. Data point numbers vary considerably between Type-2 and Type-3 data. Although the Type-3 depth measurements are highly detailed linearly, the overall coverage of the lakes is occasionally limited – due to shallow depths, vegetation, skill of operator handling the boat, weather conditions during survey etc. The number of data points and spatial coverage in Type 2 datasets were in the majority of cases sufficient, using the methods described in this report, to generate decent bathymetries. The accuracy of the location and depth data can be considered to increase from Type-1 to Type-3.

Because of boat and depth measuring operating issues i.e. working in water less than the draft of the vessel and, in the case of the ECRC-ENSIS operated GPS/echo sounder unit ceases recording at ~0.5m, the number of survey points in the 0-0.5m depth range are under-represented. The use of the lake outline (0m depth) confining the IDW grid provides some additional depth data to this critical depth zone. In some lakes the presence of marginal wetland vegetation has also restricted the spatial coverage of depth data (see future recommendations, Section 4)

The bathymetric maps produced by this work should clearly not be used for navigation. Water depths in relation to a local datum or water depths to m O.D. were recorded at only Llyn Anafon (d63) and Bosherston (d59) respectively. Determining the water level to a relative (that can be related to in the future) or specific OS datum benchmark is clearly critical for repeat and future surveys. The overall lack of datum data for this work is regrettable, but reflects the remote nature of many of the lakes surveyed. All depths reported in this document are therefore depth below water surface (m) for consistency.

2.2 Collation of electronic depth and location data. Conversion of all survey data ready for entry into GIS.

All lake data returned to CCW are stored in separate folders named accordingly: WBID_Name e.g. 32746_Llyn_Llywenan where WBID is the UKLakes (www.UKLakes.net) water body ID and Name is the accepted UKLakes water body name. These folders include raw data, interpolated grids, basic ARCMap (.mxd) files and morphometric statistical outputs. This document and other documents/spreadsheets related to the project are stored in the folder _Docs. Below is reproduced as text file: readme_lake_folder_guide.txt in the folder_Docs.

Each lake data folder contains the following:

d<datasetid>_<WBID>_xyz.csv	Raw data (comma delimited). Column headings Index, OS_X, OS_Y, Depth where depth is in metres (m).
d<datasetid>_<WBID>_xyz.shp	Shape file collection (with .prj files) from .csv data.
<foldername>_lake_polyline.shp	Lake outline polyline (derived from OS raster data, required for confining bathymetric raster).
<foldername>.mxd	Basic ArcGIS project file. Document set to relative path names.
b<bathygridid>_WBID	ESRI grid folder, bathygridid relates to individual bathymetric grid outputs. May be multiple folders. This allows flexibility to have multiple outputs dependent on settings inputted for grid calculation.
b<bathygridid>_WBID.asc	ASCII export of ESRI grid. Standard export format of raster data. Used for R: software outputs.
<foldername>_lake_polygon.shp	Occasional lake outline polygons from UKLakes database (OS 1:50000) used for comparison.

Morphometric Statistic Outputs:

b<bathygridid>_WBID_hypsographic_curve.pdf	Hypsographic curve (Depth; %area, m^2)
b<bathygridid>_WBID_depth_-_volume_curve.pdf	Depth volume curve (Depth; %volume, m^3)
b<bathygridid>_WBID_composite_display.pdf	Composite diagram from R: script output
b<bathygridid>_WBID_curve_data.csv	Volume (m^3), Area (m^2) values for 0.5m depth intervals calculated from raster grid.
Shapefiles	Folder containing polygon shapefiles for individual 0.5m depth intervals generated from the raster grid

2.2.1 Conversion of survey data to standardised xyz format

For the number (n=10) of Type-1 datasets that had no other bathymetric data source we have documented a protocol for redigitising paper copies using ARCMap software (Appendix 2).

Type-2 bathymetric data from hand-held GPS and echo sounders required only tidying the original spreadsheets and saving in .csv format. This was a relatively rapid process as Ordnance

Survey coordinates and depths were recorded in the field. In only two datasets (d8_Llyn_Mawr and d62_Llyn_y_Bi) data points were outside of the lake area. These points were noted then deleted.

Type-3 datasets from ECRC holdings required the data output from the Lowrance GPS and depth recorder to be processed. Coordinates recorded by the ECRC Lowrance system are in WGS84 format. The protocol used to convert from WGS84 to OSGB36 is documented in Appendix 3. We used the same protocol to convert WGS84 data provided by CEH and EAW for Llyn Tegid (d118), Arenig Fawr (d119), Llyn Cwellyn (d120) and Llyn Bodlyn (d121). The protocol was successful on these sites except for Llyn Bodlyn due to an as yet unresolved problem with the supplied coordinate data.

2.3 Protocol for construction of bathymetries and bathymetric data for all sites – production of grid layers, polygons, statistical outputs

Standardised OSGB Coordinate and depth data in .csv file format has been achieved for 78 individual lakes (two datasets for Llyn Anafon). This is the ‘raw data’ supplied to CCW and the basis of the IDW (Inverse Distance Weighted) Interpolation method used to generate the interpolated grid layers/ bathymetric raster data.

Appendix 4 describes the process used to generate the bathymetric data in ARCMap.

IDW creates a grid of regular-sized square cells and a modelled depth for each cell. The modelled depth is computed using actual data from data points nearby but not necessarily inside the grid cell. It is possible to constrain the interpolation to the boundaries of the lake.

IDW interpolation determines cell values using a linearly weighted combination of a set of sample points. The weight is a function of inverse distance. The surface being interpolated should be that of a locationally dependent variable.

It was immediately apparent that due to the diverse physiography of the lakes and the variable coverage of spatial and depth data, it is impractical to apply rigid input criteria – in terms of grid layer cell size, number of points used in the interpolation model, depth variables displayed for the ESRI raster, etc. Each lake bathymetric dataset was treated separately and the interpolated grid layers generated reflect subjectivity/judgement from experience.

3 RESULTS

3.1 Production of interpolated grid layer from depth survey points for all lakes

76 interpolated grid layers (bathymetric raster/ascii files) have been generated (Appendix 5). These can be found in the individual site folders, e.g. in 32640_Mynydd_Bodafon they are: b138_32640.aux (raster) and b138_32640.asc. The letter 'b' at the start of a file name indicates a file related to a bathymetry (this reflects the fact that multiple bathymetries can be generated by altering controlling IDW factors) while "d" at the start indicates which dataset it is from. The 'd' and 'b' numbers are unique. The labelling of all files is described in Section 1.2.

Metadata for the grid layers includes the method of IDW used, resolution (cell size), minimum number of points used and radius (m) of nearby points used in interpolation (Appendix 5). The IDW interpolated grid layers are bounded by a polyline lake outline. 1:25000 OS outlines were used for the majority of lakes. 1:10000 OS outlines were used for Llyn Maelog (d4), Llyn y Glas (d28), Llyn Cadarn (d35), Llyn Anafon (d36) and Llyn Coch (d40). 1:50000 OS outlines were used for Llyn Erddyn (d26) and Llyn Cwellyn (d120).

Following data conversion and reprojection, some xyz points were occasionally found to be outside of the OS outlines. This is likely a map scaling/data transformation issue. Rather than deleting the points, the lake outline was modified to encompass the points. Errors in volume/area generated by this procedure are considered to be small.

3.2 Production of polygons of 0.5m depth intervals from contouring of interpolated grid layer for each site.

The production of polygons and contours is a straightforward process in ARCGIS using the raster grid generated by the IDW method. However, similar to applying rigid input criteria to the IDW interpolation method, any polygons/contours produced depend on the IDW method and parameters used during the interpolation process. How to generate contours in ARCGIS and an example of the variation in contours produced by different resolution grid layers is shown in Appendix 4.

Individual polygon shapefiles have been generated at 0.5m depth intervals. This was achieved by converting the interpolated raster grid into a set of polygons – one for each grid cell. Adjacent cells/polygons of the same 0.5 m interval were first merged into a single polygon, while isolated polygons/cells of the same depth interval were given the same ID and linked. The merged data of the depth intervals were then converted into a single shapefile. These shapefiles are found in the individual lake folders in the sub-folder 'shapefiles'. The R: script used to generate the process can be found in the _docs folder of the Final Data Folder.

3.3 Generation of morphometric statistics from bathymetries of each lake and 0.5m depth intervals.

This has been achieved by processing raster grids using R: software (Simpson G.L., unpublished R: code – Appendix 6). The R: script uses only the data from the modelled IDW generated grid. The output model areas are therefore often less than actual lake area due to un-surveyed areas with no data. In this case actual mean depth is likely to be less. The process generates tables of area and volume calculations from the IDW generated grid and produces curves of depth/area and depth/volume for each lake. The depth/area (hypsographic curve) depth/volume curves represent the relative proportion of the bottom area/volume of the lake between depth intervals. They are only an approximation of the area/volume because measurements are relative to horizontal surfaces. Increased slope angularity generates greater surface area/volume. Depth/area and depth/volume data is calculated for each lake as a result of lake level drawdown (0.5m intervals). The file outputs from this process are found in the individual lake folders (details - Section 1.2) and attached at the end of this document (Appendix 9-11).

3.4 Multivariate summary statistics of surveyed lakes.

Data has been extracted from the UK Lakes dataset for the lakes from which a bathymetric raster was generated (listed in Appendix 8). This includes mean depth, maximum depth, shoreline development index and lake volume data from the UK Lakes dataset. Multivariate statistical analysis was performed on the morphometric parameters for the lakes in the bathymetry database. Table 3.1 contains a list of the parameters used. All variables were standardised to zero mean and unit standard deviation prior to all analyses.

Variable	
Mean Depth	Perimeter
Maximum Depth	Altitude
Volume	Shoreline Development (SDI)
Area	Maximum Fetch

Table 3.1 Variables used in the multivariate analyses

3.4.1 Cluster Analysis

A hierarchical cluster analysis using Ward's minimum variance clustering on a Euclidean distance matrix was used to investigate groupings within lakes. The resulting dendrogram (Figure 3.1) suggests the presence of two main groups of sites, plus a third, smaller group consisting of eight sites. The large fusion heights at which these three groups become merged suggest a good degree of separation in the clusters.

3.4.2 Principal Components Analysis

Principal components analysis (PCA) was performed on the morphometric data to look at patterns in the types of lake contained in the bathymetric database. PCA was performed on the correlation matrix of the data thus removing the effects of scale from the analysis. Figure 3.2 shows the resulting PCA biplot, drawn using symmetric scaling. Figure 3.2 (a) shows the entire dataset, Figure 3.2(b) focuses on the main body of lakes. Comparison with the appropriate broken stick distribution suggests two axes explain the important components of variation in the dataset, accounting for 60% and 21% variance respectively.

The first PCA axis is a function of lake size; and separates the main body of lakes in the database from several of the larger sites. The second PCA axis contrasts upland and lowland lakes; the former tend to be deeper and with low shoreline development index, whilst the latter tend to be shallower and with more developed shorelines.

Cluster 1, shown in blue on Figure 3.2 (a), is predominantly comprised of larger, deeper lakes, which are arranged around the edges of the biplot. Cluster 2, shown in black, is mainly located in the upper half of the biplot, and consists of lower lying sites with higher than average shoreline development. Cluster 3, located in the lower half of the biplot, is the opposite of Cluster 2, and represents higher altitude sites with less-well developed shorelines.

In general, however, save for the Cluster 1 sites, the sites in the database represent a continuum of lake morphology with no clear discontinuities present in the biplot. As all cluster analyses will find clusters in a data set, the PCA biplot provides a useful guard against over-interpretation of the dendrogram (Figure 3.2).

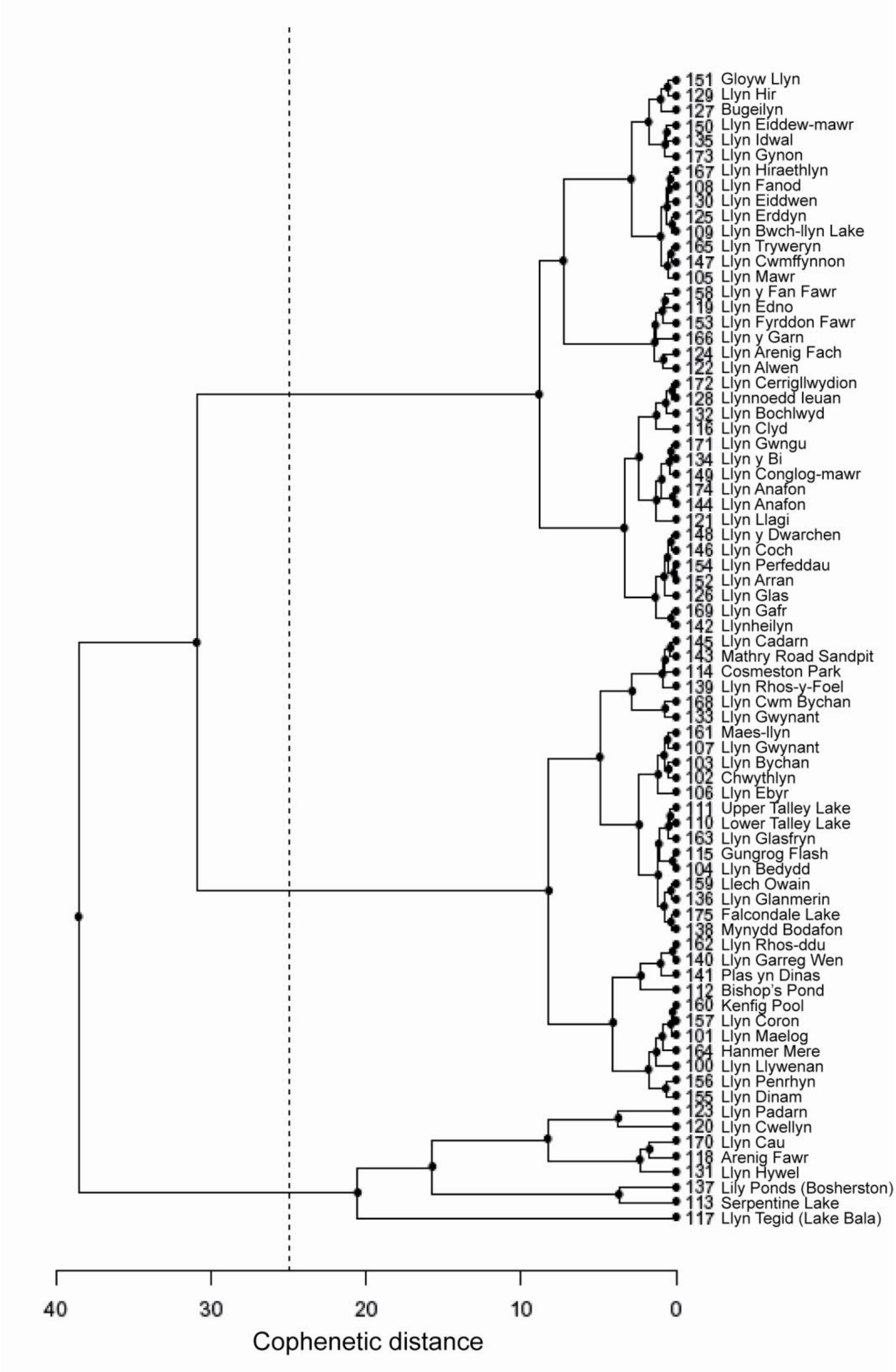


Figure 3.1 Cluster analysis dendrogram from morphometric dataset.

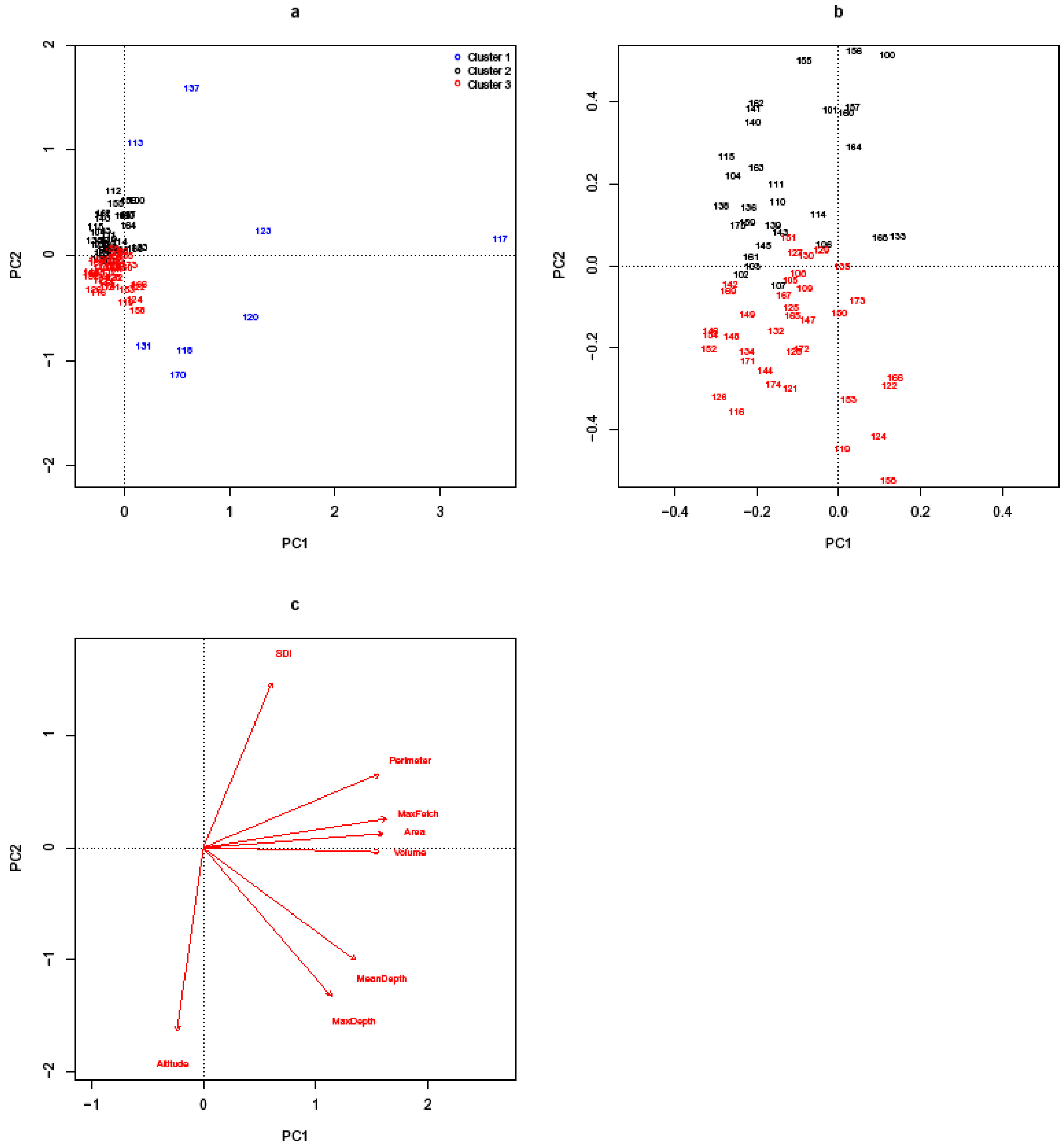


Figure 3.2 Principal Components Analysis (PCA) biplot output of morphometric data (a) and enlargement of diagram around the origin (b). Biplot arrows show the directions of increasing values of the morphometric variables ordinated.The colours indicate the cluster membership of each lake.

3.5 Uncertainty analysis and statistical modelling of bathymetric data

The approach used in the rest of the report to generate lake bathymetric maps and associated morphometric data uses an inverse distance weighting approach to interpolate the observed lake depth measurements to a regular grid. This technique, like other simple interpolation schemes, treats the depth data as effectively being sampled without error. As such, there is one bathymetry for a given set of inverse distance weighting parameters as applied in the GIS software. This can lead to irregular bathymetries that could contain artefacts of the particular set of observed data.

An alternative approach to the generation of lake bathymetries would be to treat the lake depth data as random variables whose expectation (mean) we wish to estimate as a function of the x and y coordinates. We assume the lake depth data contain a systematic component that is related to the morphometry of the lake bed, plus a stochastic error component. We further assume that the locational data are known without error. This is the familiar regression framework where we model the lake depth as a function of the location data. We can then use the statistical properties of the model to investigate uncertainties in the lake bathymetry and how these uncertainties feed through into the morphometric data etc.

For the purposes of this section of the report, we will further assume that the lake bathymetry is a smooth function in space. A natural way of modelling such data is through an additive model using 2D regression splines of the x and y locations. However, lake bathymetric data pose a particular problem for standard smoothers; namely that the splines are fitted across the entire region of interest and thus smooth across boundaries in the lake shape, such as peninsulas. As a result, we get leakage of information from one side of a feature to the other. In reference to lake bathymetries, this can induce features in the interpolated/smoothed bathymetry that are artefacts of the smoothing process. To some extent the effect of this leakage can be mitigated by introducing points on the lake boundary with known depth 0 in an attempt to constrain or force the smoother. However, this mitigation may be limited in effect if sufficiently large smoothing windows are used.

Recently there have been developments in smoothing theory that aim to solve or address this particular problem. One of these developments is the soap film smoother of Wood *et al.* (2008). Soap film smoothers take their name from the flexible films of liquid soap that form across hoops and other shapes used by performance artists. A smaller version of this is the bubble bottle children's toy, consisting of a small hoop on a stick which is dipped into a liquid soap solution over which the child blows gently to produce soap bubbles. A more useful analogy in the case of lake bathymetry modelling is to think of the soap film smoother as a sheet of flexible rubber attached to the lake outline. We can deform this rubber sheet by stretching it towards the observed data, thus forming a smoothly undulating surface from the flexible sheet. The lake outline provides a fixed boundary beyond, and across, which no smoothing is performed; the data on one side of a feature (peninsula, say) do not influence the smoother (rubber sheet) on the other side of the feature.

Soap film smoothers allow for the boundary, the lake outline, to be set to a known, fixed value of the response; here we use the value of 0 depth for the lake outline. The boundary can also be left as unknown, to be estimated from the data. In such cases, the boundary is modelled as a cyclic cubic regression spline in order to best fit the observations at the margins of the space over which smoothing is required. A cyclic smoother is used because the boundary is treated as a line with a start and end point and we wish to assume a smooth transition across the start and end points.

Soap film smoothers require some specialist software to generate the underlying basis functions that comprise the soap film, but these smoothers can be plugged into standard additive modelling software and treated just like any other smoother fitted using a penalised regression to determine the optimum degree of smoothing required. Here we use the `soapfilm` package (Wood *et al.* 2008) in conjunction with the `mgcv` additive modelling package (Wood 2004, 2008), both for the R statistical software.

The soap film smoother, as with the other types of smoother that can be fitted using mgcv, is defined by a series of coefficients. The software estimates the values of these coefficients from the observed data points. These estimates have associated standard errors.

The coefficients and their covariance matrix define a multivariate normal distribution, from which we are able to sample random sets of coefficients that are consistent with the estimated soap film smoother. In doing this we are in effect generating repeated lake bathymetries that are consistent with the best fitting bathymetry but which explore the uncertainty in that best fitting version. This process is known as sampling from the posterior distribution of the model parameters and is a standard approach in statistics to investigate fitted models and to create credible (confidence) intervals.

We illustrate the soap film approach using two examples; i) the 2009 survey of Llyn Anafon, and ii) the survey of Cosmeston Park Lake. The former example demonstrates the performance of the soap film smoother for standard lake shapes, whilst the latter illustrates the performance of the soap film smoother with a very irregular lake outline and the presence of a feature, separating two basins of the lake, across which we do not want to smooth.

The R script used for this approach can be found in Appendix 12.

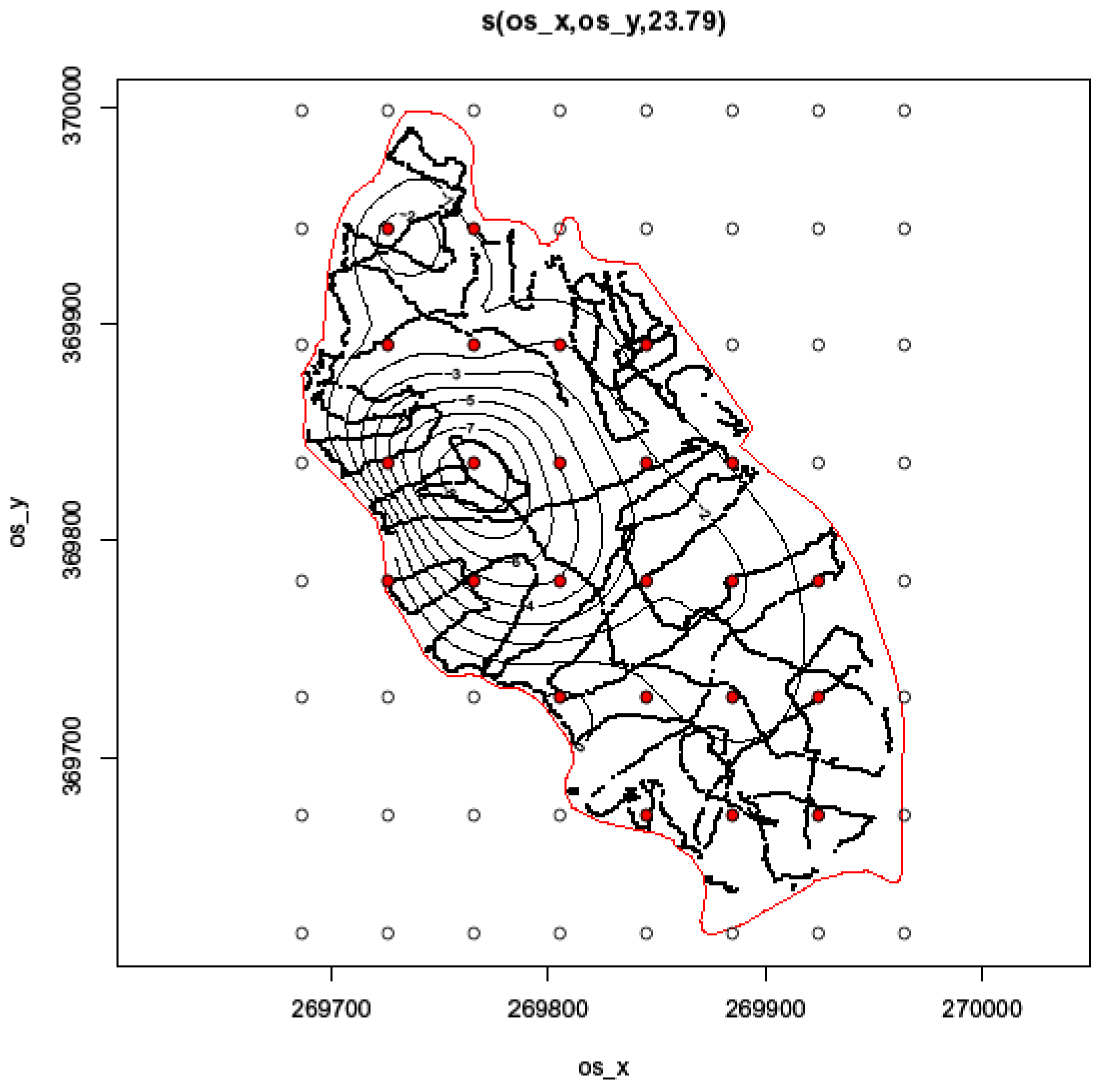


Figure 3.3 Illustration of the soap film smoother approach. The individual depth measurements for the Llyn Anafon 2009 survey (d59, b174) are shown (small dots). The thick, solid line is the lake outline, which is used as the boundary for the soap film. Open circles represent a regular grid of candidate knots, located evenly across the full geographical range of the observed depths. The filled circles are those candidate knot locations that are found inside the boundary. The solid contours are the values of the soap film smoother observed on a fine grid over the region of interest. Note that the smoother is centred and we have treated depth as a negative value, such that increasing negative values indicate increasing depth.

File name: soap-film_illustration_anafon.pdf

Soap film smoothers were fitted to the two lake bathymetry data sets using a small number of knots. We first define a regular grid of candidate knot locations spread evenly across the spatial region of interest (open circles in Figure 3). We then locate those candidate knot locations that lie within the lake boundary (filled circles in Figure 3). The lake outline is supplied as the boundary support for the soap film. A centred soap film smoother is then parametrise on the supplied knot locations and boundary using a P-spline basis. The fitted additive model therefore consists of a parametric intercept term, and 2D soap film smoother of the x- and y-coordinates of the individual lake depth measurements. As such, the method requires no additional data beyond the depth data, sample locations and a lake outline. The entire process is illustrated in Figure 3 for Llyn Anafon showing the fitted, centred soap film smoother (contours), the chosen knot locations and the raw depth data.

The soap films fitted to the two lake depth data sets are reasonably simple smoothers, using only a modest number of degrees of freedom (Table 3.2) relative to the available degrees of freedom, yet provide good fits (very good in the case of Llyn Anafon) to the observed lake depth data. The two fitted soap film bathymetries are shown in the upper left panels of Figures 3.4 and 3.5. Notice how these bathymetries are much smoother than those produced by the inverse distance weighting procedure (Appendix 9). This is a feature of the smoothing approach we have used here; the irregularity is assigned to the stochastic error component of the model.

Lake	DF	Deviance Explained	F	p-value
Llyn Anafon (2009)	23.99	91.4%	2353	<< 0.001
Cosmeston Park Lake	20.77	73.4%	31.29	<< 0.001

Table 3.2: Soap film data fitted to Llyn Anafon and Cosmeston Park Lake

To investigate uncertainty in the fitted bathymetries and how these uncertainties feed through into some of the morphometric derived measures, we drew 1000 random samples from the posterior distribution of the parameters of the soap film models for each lake. We then computed the 99% credible (confidence) region for the two fitted smoothers from the 1000 random samples. This was performed on a 5m by 5m regular grid across the entire region of each lake, leading to a gridded bathymetry for each lake, predicted from the fitted soap film model, with a 99% credible interval on the predicted depth value produced for each grid cell.

The 99% credible (confidence) regions are show in the lower panels of Figures 3.4 and 3.5 for Llyn Anafon and Cosmeston Park Lake respectively. Given the large amount of data and close degree of fit in the smoother applied to Llyn Anafon, the predicted bathymetry for this lake is reasonably consistent, with the 99% credible region suggesting little systematic variation beyond slight deepening and shallowing of the basin in the upper and lower regions respectively.

The lower level of fit to the available data in the Cosmeston Park Lake soap film smoother exhibits greater uncertainty in the predicted bathymetry, likely arising from the lower level of data coverage in this site. The upper 99% credible region suggests a much larger zone of ~10m depth is consistent with the fitted model. Only 7 of the depth observations in Cosmeston Park Lake were in the 9.5-10m depth interval. However, given the spread of these points in space plus the other measurements near to these deepest observations and the inherent uncertainty in the shape of the basin that this imparts, we have no statistical reason to disregard the credible region at this site. Collection of additional data in a manner similar to Llyn Anafon, with a high degree of coverage at a fine spatial scale and large number of observations, particularly in the lake margins, would reduce the uncertainty in the resource that is apparent in Cosmeston Park Lake.

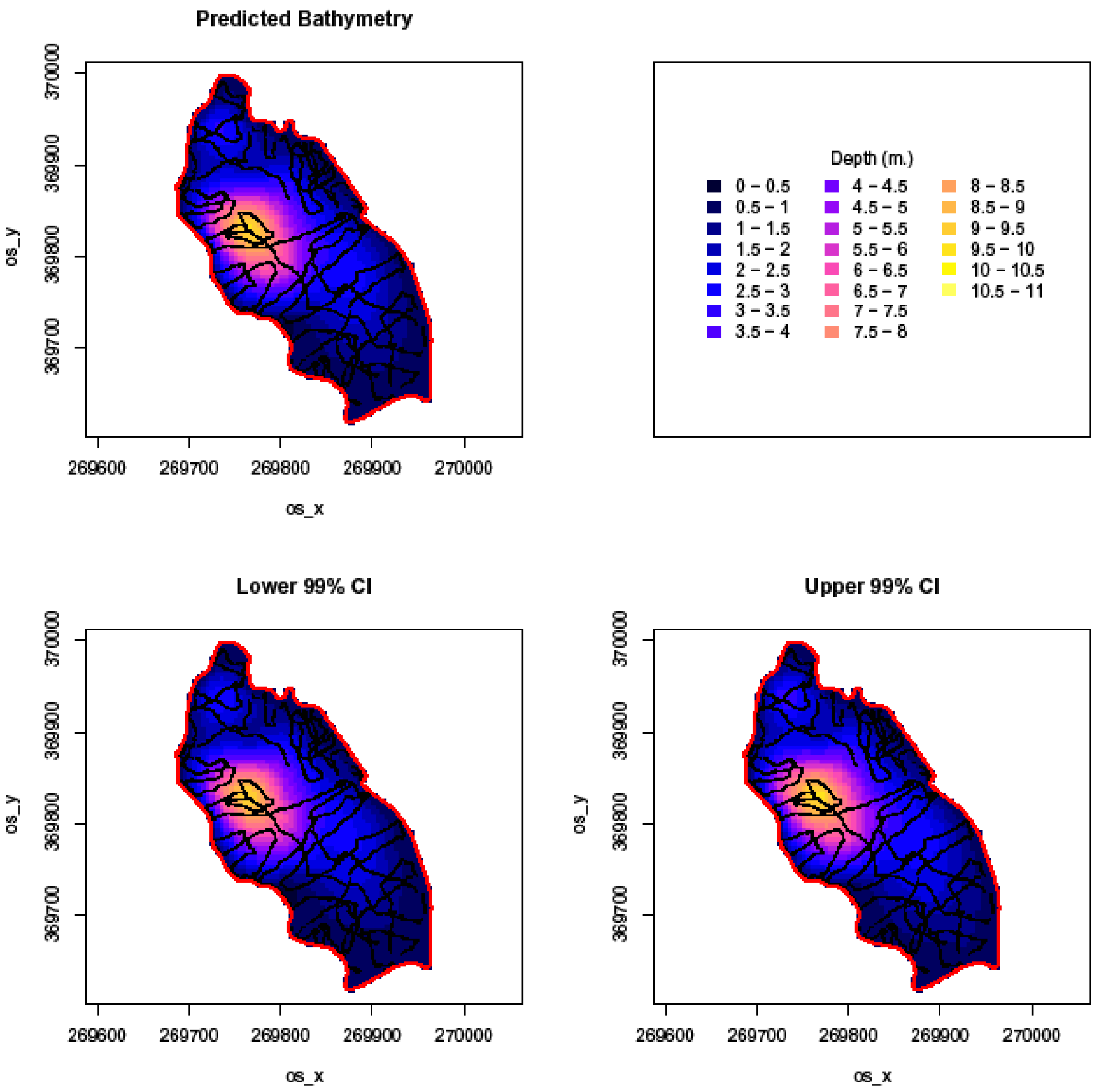


Figure 3.4 Predicted bathymetry (upper left) and lower (lower left) and upper (lower right) 99% credible regions based on the soap film smoother methodology for Llyn Anafon. Predictions are on a 5m by 5m grid over the region of the lake.

File name: 4up_layout_anafon.pdf

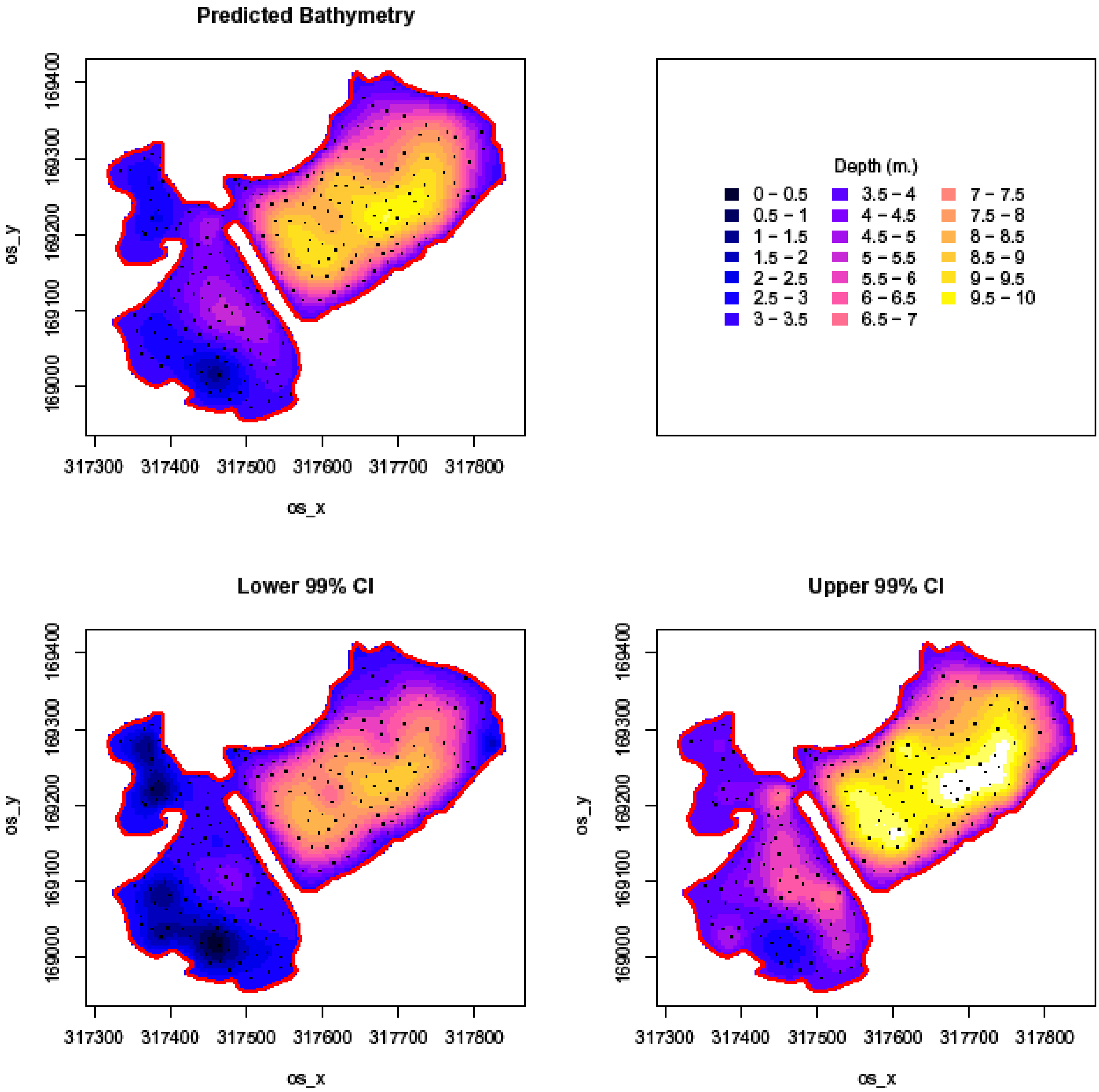


Figure 3.5 Predicted bathymetry (upper left) and lower (lower left) and upper (lower right) 99% credible regions based on the soap film smoother methodology for Cosmeston Park Lake. Predictions are on a 5m by 5m grid over the region of the lake.

File name: 4up_layout_cosmeston.pdf

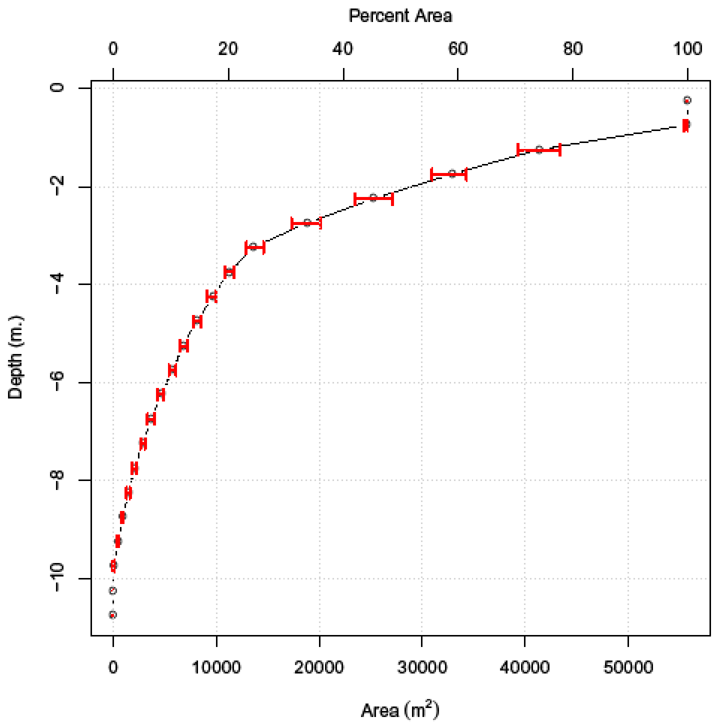


Figure 3.6 Area-depth curve for the soap film smoother predicted bathymetry for Llyn Anafon. The error bars encompass the 99% credible region about the area-depth curve, based on sampling from the posterior distribution of the soap film model parameters. File Name: area_depth_curve_uncertainty_anafon.pdf

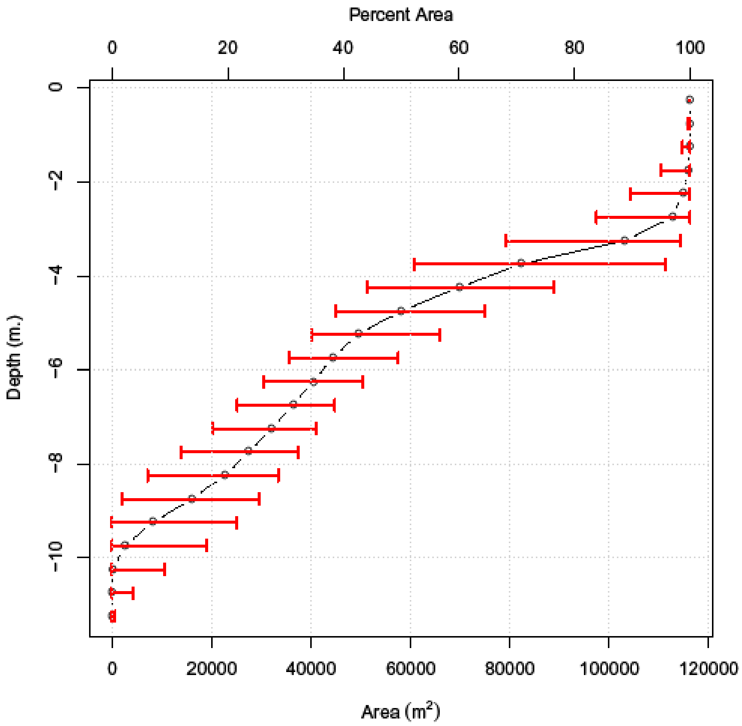


Figure 3.7 Area-depth curve for the soap film smoother predicted bathymetry for Cosmeston Park Lake. The error bars encompass the 99% credible region about the area-depth curve, based on sampling from the posterior distribution of the soap film model parameters. File name: area_depth_curve_uncertainty_cosmeston.pdf

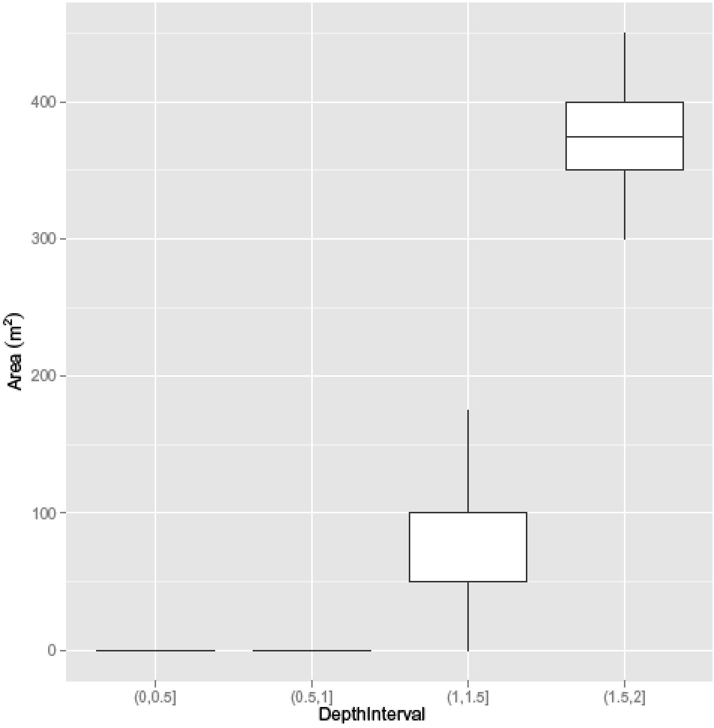


Figure 3.8 Boxplots showing the area of Llyn Anafon in each of the 0 – 2m depth intervals for the 1000 draws from the posterior distribution of the soap film model parameters. File name: area_in_0-2_classes_anafon.pdf

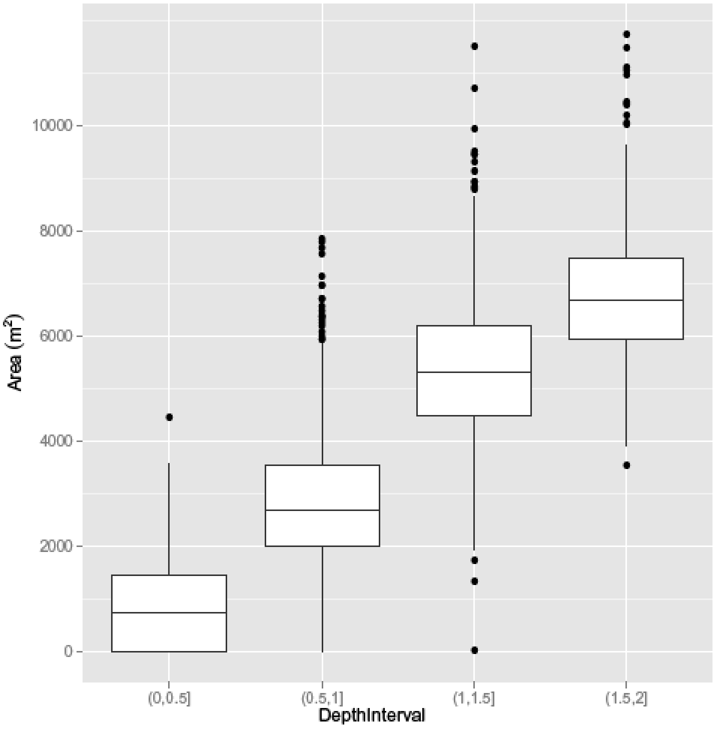


Figure 3.9 Boxplots showing the area of Cosmeston Park Lake in each of the 0 – 2m depth intervals for the 1000 draws from the posterior distribution of the soap film model parameters. File name: area_in_0-2_classes_cosmestong.pdf

A further feature of note in Figure 3.5 is the behaviour of the smoother around the peninsula feature in Cosmeston Park Lake. Notice how the fitted smoother approaches the feature in a natural manner, with depth contours parallel to the feature. There is also no leakage of information from one side of the feature to the other. Contrast this with the inverse distance weighted bathymetry in Appendix 10. Qualitatively then, these two methods of producing a bathymetry yield different descriptions of the basin shape.

Random sampling from the posterior distribution of the parameters effectively yields 1000 bathymetries per lake. We can use these bathymetries to investigate uncertainty in the derived morphometric variables and results. To this end, we illustrate a couple of additional analyses that can be facilitated through the use of a statistical approach to bathymetric modelling. First we computed area-depth curves for the predicted bathymetry and it's 99% credible region for both lakes. These are shown as error bars about the predicted area-depth relationship in Figures 3.6 and 3.7 for Llyn Anafon and Cosmeston Park Lake respectively. However, because of the relatively small amount of lake area in the shallower depth categories, a feature particularly apparent in Llyn Anafon, we also compute separately the actual area of the lake in the 0-2m depth range (in 0.5m intervals) and show these as boxplots of the 1000 posterior draws for each site (Figures 8 and 9) in Llyn Anafon, we note very little variation across the posterior draws in the 0-1m depth range, whilst the 1-2m depth range shows considerably greater variation. The 1-1.5m range is particularly interesting, with the posterior draws suggesting the possibility that there is presently very little area of the lake in this depth range, although if draw down were to proceed slowly to allow time for aquatic macrophytes to migrate to “deeper” zones, there is significant area of the lake in slightly deeper levels (1.5-2m for example) for suitable habitat to be found.

As a final example, we produce depth-volume curves for the two lakes' predicted bathymetry (Figure 3.10 and 3.11). The curve for Llyn Anafon is drawn using error bars, as per the depth-area curves presented above, whilst the curve for Cosmeston Park Lake is presented as a series of 3 curves representing the upper and lower 99% credible curves respectively. Because of the greater level of uncertainty in the predicted bathymetry for Cosmeston Park Lake, significant lake volume jumps between the depth-interval classes used to produce the depth-volume curve. As the curve is presented as cumulative volume (as is convention), this results in reversals in the upper and lower 99% credible curves, and even to a situation where the curve for the predicted bathymetry lies *outside* the “region” defined by the upper and lower 99% credible curves. We present these two versions as alternative means for displaying the uncertainty in depth-volume measurements and to highlight the potential difficulties of representing the uncertainty using error bars. This issue may also crop up in the depth-area curves for particularly uncertain bathymetries.

Soapfilm smoothers could be used routinely by conservation agencies, although some previous experience with smoothers and additive models would be useful. The technique we illustrate is only available via the soapfilm package for the R statistical language. This package requires the mgcv package for fitting additive models. The soapfilm package is available from Simon Wood's website: http://www.maths.bath.ac.uk/~sw283/simon/software.html

We provide a commented script (Appendix 12) to illustrate how to fit a soapfilm smoother to the Llyn Anafon depth soundings, including all the intermediate data processing steps required to set up the soapfilm. The soapfilm itself is fitted via this function call:

```
m2 <- gam(-Depth ~ s(os_x, os_y, k = 10, bs = "so", xt = list(bnd = bound)),
        data = depth, method = "REML", knots = knots)
```

'-Depth' is the negative of the water depth, taking 0 as the lake surface. The remainder of the first line is how the soapfilm is defined; 'os_x' and 'os_y' are the GB OS coordinates (easting and northing respectively), 'k' controls the complexity of the fitted soapfilm and is a key parameter to tweak - it represents an upper bound on the complexity (wiggly-ness) of the fitted bathymetry as the software will select the optimal wiggly-ness during fitting. The value of 'k used ('10') proved suitable for the two fitted surfaces we describe in the report. The remaining information is specific to the soapfilm - 'xt' is where we pass in information about the lake outline. The second line of code shown informs R where to find the data needed to fit the model, here stored in an object named 'depth' ('data = depth'), how to select the complexity of the surface, here using restricted maximum likelihood ('method = "REML"'), and the locations of the knots from which to build the soapfilm. All of these objects are defined in the script prior to fitting the soapfilm.

If a user formats their data and follows the script using the same object names and function calls, they should have little difficulty in fitting a soapfilm smoother. However, like any modern statistical method, an understanding of fitting statistical models and model diagnostics is required to apply these methods appropriately.

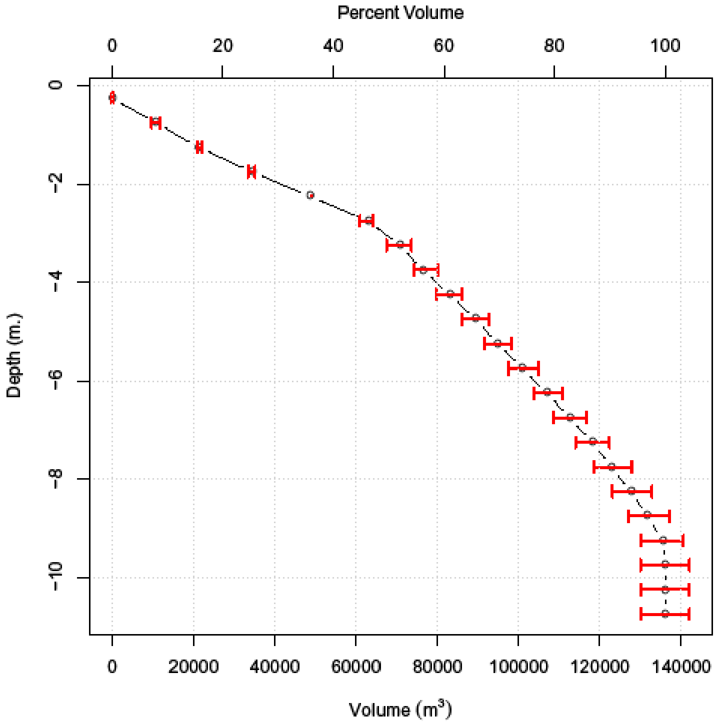


Figure 3.10 Depth-volume curve for the soap film smoother predicted bathymetry for Llyn Anafon. The error bars encompass the 99% credible region about the depth-volume curve, based on sampling from the posterior distribution of the soap film model parameters. File name: depth_volume_curve_uncertainty_anafon.pdf

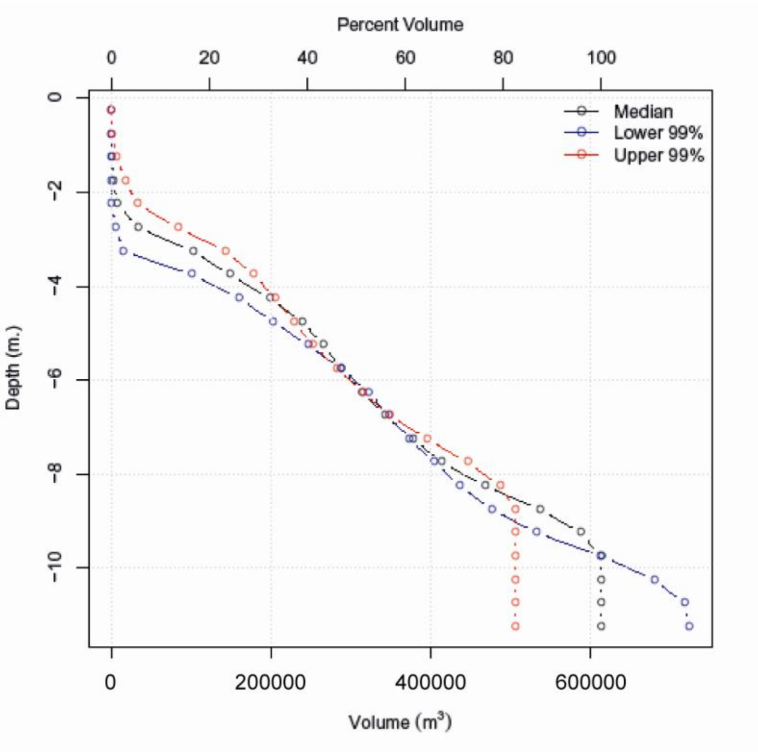


Figure 3.11 Depth-volume curve for the soap film smoother predicted bathymetry for Cosmeston Park Lake. Depth-volume curves for the upper and lower 99% credible intervals are shown, based on sampling from the posterior distribution of the soap film model parameters. File name: depth_volume_curve_uncertainty_cosmeston.pdf

4 DISCUSSION

This work has been a laborious process due to the retrospective nature of the project and physical demands of working-up raw data for a significant number of lakes. For many of the lakes that we have generated bathymetric data for it is clear that due to the imperfect raw data, i.e. the unknown extent of water depths less than 0.5m, error in recording depths due to the actual nature of the substrate (suspended sediment/plant beds) and extent of shoreline/wetland lake margin the values we have calculated should be used with a degree of caution, certainly for any navigation purposes.

Table 4.1. Lakes in dataset (D) with no data due to loss, unsuitable format and data not forthcoming

D	WBID	Lake Name	Surveyor	Data	Method	Status
1	**32435**	Llyn Llygeirian	?	?	?	Unknown
2	**38409**	Llyn Egnant	?	?	?	Unknown
34	**32761**	Llyn yr Wyth-Eidion	ECRC	point	Boat GPS/Echo	Data lost
41	**34531**	Llyn Hesgyn	ECRC	point	Boat GPS/Echo	Data lost
58	**40297**	Llyn y Fan Fawr	ECRC	point	Boat GPS/Echo	Data lost
64	**34033**	Llyn Llydaw	Jehu 1902	contour	Sounding line	Paper only
65	**33828**	Llyn Peris	Jehu 1902	contour	Sounding line	Paper only
66	**34002**	Llyn Cwellyn	Jehu 1902	contour	Sounding line	Paper only
67	**34244**	Llyn Dinas	Jehu 1902	contour	Sounding line	Paper only
68	**33762**	Llyn Crafnant	Jehu 1902	contour	Sounding line	Paper only
70	**35550**	Llyn Dulyn	Jehu 1902	contour	Sounding line	Paper only
71	**33765**	Llyn Geirionydd	Jehu 1902	contour	Sounding line	Paper only
72	**33571**	Llyn Eigiau (Res.)	Jehu 1902	contour	Sounding line	Paper only
73	**33686**	Llyn Cowlyd (Res.)	Jehu 1902	contour	Sounding line	Paper only
90	**40067**	Llangorse Lake	M3	contour	Unknown	scan only
93	**41210**	Llyn Fach	M3	contour	Unknown	scan only
95	**32761**	Llyn yr Wyth-Eidion	M4	contour	Unknown	scan only
97	**33932**	Llynnau Mymbyr	M4	contour	Unknown	scan only
107	**33073**	Llyn Pen-y-Parc	W1	?	Unknown	no data
108	**34397**	Llyn Cwmorthin	W1	?	Unknown	no data
109	**34614**	Llyn Du	W1	?	Unknown	no data
112	**34929**	Llyn Tecwyn Isaf	W1	?	Unknown	no data
114	**36021**	Llyn Gwernan	W1	?	Unknown	no data
121	**35561**	Llyn Bodlyn	EAW	point	hydroacoustic	Data issue

The number of lakes from the compiled dataset that did not have a bathymetric grid generated are shown in Table 4.1. The principal cause is that the bathymetric data in reports/papers correspond to contours drawn for historical survey i.e. Jehu (1902) or sketched/ redrawn from Ordnance Survey bathymetric survey. It is unfortunate that due to a historical failure in data storage the original boat GPS/Echo data from Llyn yr Wyth-Eidion, Llyn Hesgyn and Llyn y Fan Fawr have been lost.

4.1 Recommendations

4.1.1 Survey and Data Collection

- We recommend that the lakes listed in Table 4.1 be resurveyed and point data retrieved and fed through the methods described in this report. Similarly for when/if data is made available from recent work, i.e. Wade *et al.* (in prep).

- For future work and to generate the best possible bathymetric models, great care should be taken when collecting and recordingdata in the field. Every effort should be made to cover as much of the lake as possible with data points regularly spaced and as close to the edge as possible. The detail of work conducted at Bosherston (Holman *et al*. 2007) and at

Llyn Anafon (Goldsmith *et al.* 2009) should be regarded as a standard level of investigation.

- For all future survey work, recording lake levels in relation to an OS benchmark or identifiable and stable local datum is highly recommended. Meaningful use of bathymetric data in terms of monitoring, aquatic habitat preservation, effects of water drawdown due to water abstraction and climate/hydrological changes rely on such.

- During the bathymetric survey, the water level should be recorded in relation to a datum. If possible the lake shoreline boundary should also be recorded. Where conditions allow a survey of the shallow areas (<0.5 – 1m) should be carried out. This can be done by wading or from a boat using a GPS and rule. The extent and water depth within wetland areas surrounding a lake should also be measured to provide greater detail of the overall hydrology of the lake and sensitivity of marginal areas to water level changes.

4.1.2 Data Storage and Archiving

- We would recommend that because of continual software development, a key component of this report has been the collection and generation of raw tabular xyz data of coordinates and depths. The .csv text files allow the data to be used and manipulated across software platforms.

- Any reporting of bathymetric data must include this raw data in the report as an appendix as well as with accompanying data storage formats.

- A metadata recording form to accompany the bathymetric data is highly recommended.

5 ACKNOWLEDGEMENTS

Bathymetric data is theoretically easy to collect, but to do it well takes considerable effort and skill. ENSIS and the ECRC have been lucky to have a number of individuals without whose talent in boat handling and fieldwork would have made this work impossible. It is one thing to carry a boat to a lake up the side of a Welsh mountain, but to go out on it in all weather and row systematically to and fro across the lake requires special fortitude. We gratefully acknowledge the efforts of James Shilland, Ben Goldsmith, Ewan Shilland and the many other members of the ECRC who assisted in the data collection.

We also gratefully acknowledge the efforts of individuals from the Centre of Ecology and Hydrology (CEH Lancaster), the Environment Agency (EA), Countryside Council for Wales (CCW), Cranfield University and RPS Group Plc.

6 REFERENCES

Allott, T.E.H., Monteith D.T., Patrick, S.T., Duigan, C.A., Lancaster, J., Seda, M., Kirika, A., Bennion, H. & Harriman, R. (1994). *Integrated Classification and Assessment of Lakes in Wales: Phase I*. CCW Science Report No. 85. Countryside Council for Wales. Contract No. FC 73-01-71

Burgess A, Goldsmith B, Hatton-Ellis T, Hughes M, Shilland E. (2009). *CCW Standing Waters SSSI Monitoring 2007-08*. CCW Contract Science Report 855. Bangor, Countryside Council for Wales.

Fritz, S.C., A.C. Stevenson, S.T. Patrick, B. Rippey, P.G. Appleby, F. Oldfield, J. Darley, S.R. Higgitt, R.W. Battarbee & P.J. Raven. (1986). *Palaeoecological Evaluation of Recent Acidification of Welsh Lakes: 1, Llyn Hir, Dyfed.* Palaeoecology Research Unit, University College London

Goldsmith B, Bennion H, Hughes M, Jones V, Rose C, Simpson G. (2006). *Integrating Habitats Directive and Water Framework Directive Monitoring: Baseline Survey of Natura 2000 Standing Water Habitats in Wales.* CCW Contract Science Report 704. Bangor, Countryside Council for Wales.

Goldsmith, B., Hughes, M. & Shilland, E. (2009). *Habitats Directive assessment of Llyn Anafon with respect to proposed water level changes*. Final Report to Mott MacDonald. ECRC Research Report 138.

Goldsmith, B., Burgess, A., Bennion, H., Turner, S. D., Appleby, P. G. & Piliposian, G. T. (2010). *Palaeoecological and surface sediment analysis of Welsh SSSI / SAC lakes incorporating chemical and bathymetric surveys*. Report to CCW as part of Lake Macrophyte & Habitat Surveys for the Water Framework Directive, 2007-10. The Environment Agency. Contract No: 20457

Holman IP, Gill A.B, Seymour I, Vale M. (2007). *Investigative Survey of Sediment Depth and Bathymetry of Bosherston Lakes, Pembrokeshire*. CCW Regional Report WW/07/6. Aberystwyth, Countryside Council for Wales.

Howe, G.M. and Yates, R.A.. (1953). A bathymetrical and geological study of Llyn Cau, Cader Idris. *Geography*, 38, 124-131.

Jehu, T.J. (1902). A Bathymetrical and Geological Study of the Lakes of Snowdonia and Eastern Carnarvonshire. *Transactions of the Royal Society of Edinburgh*, XL, 419-467

Monteith D.T. (ed) (1997). *Integrated Classification and Assessment of Lakes in Wales: Phase IV*. CCW Science Report No. 214. Bangor, Countryside Council for Wales. Contract No. FC 73-01-71

Monteith, D.T. (ed) (1996). *Integrated Classification and Assessment of Welsh Lakes: Phase III.* CCW Science Report No. 167. Bangor, Countryside Council for Wales. Contract No. FC 73-01-71

Monteith D.T. (ed) (1995). *Integrated Classification and Assessment of Lakes in Wales: Phase II.* CCW Science Report No. 128. Bangor, Countryside Council for Wales. Contract No. FC 73-01-71

Patrick, S.T., S.C. Fritz, A.C. Stevenson, P.G. Appleby, F. Oldfield, B. Rippey, J. Darley, R.W. Battarbee, S.R. Higgitt & P.J. Raven. (1987). *Palaeoecological Evaluation of Recent Acidification of Welsh Lakes: 9, Llyn Llagi, Gwynedd*. Palaeoecology Research Unit, University College London

Perrow M.R, Sayer C.D, Skeate E.R, Shilland E.M, Goldsmith B.J, Hughes M.J. (2004). *The future management of Falcondale Lake, Site of Special Scientific Interest, Ceredigion.* CCW Contract Science Report 620. Bangor, Countryside Council for Wales.

Wetzel, R.G. (2001). *Limnology; Lake and River Ecosytems.* Elsvier Academic Press, San Diego.

Wood, S.N. (2004) Stable and efficient multiple smoothing parameter estimation for generalized additive models. *Journal of the American Statistical Association*. 99:673-686.

Wood, S.N. (2008) Fast stable direct fitting and smoothness selection for generalized additive models. *Journal of the Royal Statistical Society* (B) 70(3):495-518

.

Wood, S.N., Bravington, M.V., & Hedley, S.L. (2008) Soap film smoothing. *Journal of the Royal Statistical Society* (B) 70(5):931-955.

APPENDIX 1: Bathymetric data holdings collated as of July 2010.

KEY
d – Dataset ID; WBID – Water Body Identification ID; Lake Name; b – bathymetry ID
Raw data – See Data collation methodology Section 2.1
OS_xyz – Raw data file of OS cartesian x,y and z (depth) generated (Y/N)

Table A1.1 Bathymetric data holdings collated as of July 2010

d	WBID	Lake Name	b	Source	Raw data	OS_xyz
1	32435	*Llyn Llygeirian*	-	N	Type 0	N
2	38409	*Llyn Egnant*	-	N	Type 0	N
3	32746	*Llyn Llywenan*	100	B1	Type 3	Y
4	33160	*Llyn Maelog*	101	B1	Type 3	Y
5	33631	*Chwythlyn*	102	B1	Type 2	Y
6	33864	*Llyn Bychan*	103	B1	Type 3	Y
7	34813	*Llyn Bedydd*	104	B1	Type 3	Y
8	37168	*Llyn Mawr*	105	B1	Type 2	Y
9	37617	*Llyn Ebyr*	106	B1	Type 1	Y
10	38321	*Gwynllyn*	107	B1	Type 1	Y
11	38544	*Llyn Fanod*	108	B1	Type 3	Y
12	39267	*Llan Bwch-llyn Lake*	109	B1	Type 2	Y
13	39796	*Lower Talley Lake*	110	B1	Type 2	Y
14	39813	*Upper Talley Lake*	111	B1	Type 2	Y
15	40338	*Bishop's Pond*	112	B1	Type 2	Y
16	41973	*Serpentine Lake*	113	B1	Type 2	Y
17	42721	*Cosmeston Park*	114	B1	Type 2	Y
18	36535	*Gungrog Flash*	115	B1	Type 1	Y
19	33730	*Llyn Padarn*	123	ECRC	Type 3	Y
20	33843	*Llyn Clyd*	116	ECRC	Type 3	Y
21	33962	*Llyn Alwen*	122	ECRC	Type 3	Y
22	34243	*Llyn Edno*	119	ECRC	Type 3	Y
23	34319	*Llyn Llagi*	121	ECRC	Type 3	Y
24	34633	*Llyn Arenig Fach*	124	ECRC	Type 3	Y
25	35426	*Llyn Hywel*	131	ECRC	Type 2	Y
26	35650	*Llyn Erddyn*	125	ECRC	Type 3	Y
27	37080	*Llyn Glanmerin*	136	ECRC	Type 3	Y
28	34044	*Llyn Glas*	126	ECRC	Type 3	Y
29	37437	*Bugeilyn*	127	ECRC	Type 3	Y
30	37834	*Llynnoedd Ieuan*	128	ECRC	Type 3	Y
31	38394	*Llyn Hir*	129	ECRC	Type 3	Y
32	38422	*Llyn Eiddwen*	130	ECRC	Type 3	Y
33	41602	*Lily Ponds (Bosherston)*	-	G1	Type 3	N
34	32761	*Llyn yr Wyth-Eidion*	-	ECRC	Type 0	N
35	32792	*Llyn Cadarn*	145	G1	Type 3	Y
36	33374	*Llyn Anafon*	144	ECRC	Type 2	Y
37	33803	*Llyn Ogwen*	-	G1	Type 3	Y
38	33836	*Llyn Idwal*	135	G1	Type 3	Y
39	33974	*Llyn Cwmffynnon*	147	G1	Type 3	Y
40	34051	*Llyn Coch*	146	G1	Type 3	Y
41	34531	*Llyn Hesgyn*	-	G1	Type 3	Y
42	34632	*Llyn y Dywarchen*	148	G1	Type 3	Y
43	34845	*Llyn Conglog-mawr*	149	G1	Type 3	Y
44	34854	*Llyn Tryweryn*	165	G1	Type 3	Y
45	34895	*Llyn y Garn*	166	G1	Type 3	Y
46	34928	*Llyn Hiraethlyn*	167	G1	Type 3	Y
47	35056	*Llyn Eiddew-mawr*	150	G1	Type 3	Y
48	35180	*Llyn Cwm Bychan*	168	G1	Type 3	Y
49	35233	*Gloyw Lyn*	151	G1	Type 3	Y
50	35444	*Llyn Perfeddau*	154	G1	Type 3	Y
51	36159	*Llyn Gafr*	169	G1	Type 3	Y
52	36177	*Llyn Arran*	152	G1	Type 3	Y

d	WBID	Lake Name	b	Source	Raw data	OS_xyz
53	36267	*Llyn Cau*	170	G1	Type 3	Y
54	38163	*Llyn Gwngu*	171	G1	Type 3	Y
55	38240	*Llyn Fyrddon Fawr*	153	G1	Type 3	Y
56	38282	*Llyn Cerrigllwydion Isaf*	172	G1	Type 3	Y
57	38525	*Llyn Gynon*	173	G1	Type 3	Y
58	40297	*Llyn y Fan Fawr*	-	ECRC	Type 0	N
59	33374	*Llyn Anafon*	174	G2	Type 3	Y
60	33862	*Llyn Bochlwyd*	132	G3	Type 2	Y
61	34153	*Llyn Gwynant*	133	G3	Type 2	Y
62	35439	*Llyn y Bi*	134	G3	Type 2	Y
63	41602	*Lily Ponds (Bosherston)*	137	H1	Type 2	Y
64	34033	*Llyn Llydaw*	-	J1	Type 4	N
65	33828	*Llyn Peris*	-	J1	Type 4	N
66	34002	*Llyn Cwellyn*	-	J1	Type 4	N
67	34244	*Llyn Dinas*	-	J1	Type 4	N
68	33762	*Llyn Crafnant*	-	J1	Type 4	N
69	33962	*Llyn Alwen*	-	J1	Type 4	N
70	35550	*Llyn Dulyn*	-	J1	Type 4	N
71	33765	*Llyn Geirionydd*	-	J1	Type 4	N
72	33571	*Llyn Eigiau Reservoir*	-	J1	Type 4	N
73	33686	*Llyn Cowlyd Reservoir*	-	J1	Type 4	N
74	32948	*Llyn Dinam*	155	M1	Type 1	Y
75	32968	*Llyn Penrhyn*	156	M1	Type 1	Y
76	33337	*Llyn Coron*	157	M1	Type 1	Y
77	33836	*Llyn Idwal*	-	M1	Type 1	N
78	34002	*Llyn Cwellyn*	-	M1	Type 4	N
79	37080	*Llyn Glanmerin*	-	M2	Type 1	N
80	37437	*Bugeilyn*	-	M2	Type 1	N
81	37834	*Llynnoedd Ieuan*	-	M2	Type 1	N
82	38394	*Llyn Hir*	-	F86	Type 4	N
83	38422	*Llyn Eiddwen*	-	M2	Type 1	N
84	38525	*Llyn Gynon*	-	S86	Type 4	N
85	38544	*Llyn Fanod*	-	M2	Type 1	N
86	38623	*Maes-llyn*	161	M2	Type 1	Y
87	39796	*Lower Talley Lake*	-	M2	Type 1	N
88	39813	*Upper Talley Lake*	-	M2	Type 1	N
89	39267	*Llan Bwch-llyn Lake*	-	M3	Type 1	N
90	40067	*Llangorse Lake*	-	M3	Type 4	N
91	40297	*Llyn y Fan Fawr*	158	M3	Type 1	Y
92	40571	*Llech Owain*	159	M3	Type 1	Y
93	41210	*Llyn Fach*	-	M3	Type 4	N
94	42170	*Kenfig Pool*	160	M3	Type 1	Y
95	32761	*Llyn yr Wyth-Eidion*	-	M4	Type 4	N
96	33627	*Llyn Rhos-ddu*	162	M4	Type 1	Y
97	33932	*Llynnau Mymbyr*	-	M4	Type 4	N
98	33962	*Llyn Alwen*	-	M4	Type 1	N
99	34319	*Llyn Llagi*	-	P87	Type 4	N
100	34622	*Llyn Glasfryn*	163	M4	Type 1	Y
101	34780	*Hanmer Mere*	164	M4	Type 1	Y
102	34987	*Llyn Tegid / Lake Bala*	-	M4	Type 4	N
103	35233	*Gloyw Lyn*	-	M4	Type 1	N
104	36267	*Llyn Cau*	-	HY86	Type 4	N
105	39154	*Falcondale Lake*	175	P1	Type 2	Y
106	32640	*Mynydd Bodafon*	138	W1	Type 2	Y
107	33073	*Llyn Pen-y-Parc*	-	W1	Type 0	N
108	34397	*Llyn Cwmorthin*	-	W1	Type 0	N
109	34614	*Llyn Du*	-	W1	Type 0	N
110	34821	*Llyn Rhos-y-Foel*	139	W1	Type 2	Y
111	34916	*Llyn Garreg Wen*	140	W1	Type 2	Y
112	34929	*Llyn Tecwyn Isaf*	-	W1	Type 0	N
113	35834	*Plas yn Dinas*	141	W1	Type 2	Y
114	36021	*Llyn Gwernan*	-	W1	Type 0	N

d	WBID	Lake Name	b	Source	Raw data	OS_xyz
115	37197	*Llyn Du*	-	W1	Type 2	Y
116	38856	*Llynheilyn*	142	W1	Type 2	Y
117	39890	*Mathry Road Sandpit*	143	W1	Type 2	Y
118	34987	*Llyn Tegid / Lake Bala*	117	CEH	Type 3	Y
119	34864	*Arenig Fawr*	118	CEH	Type 3	Y
120	34002	*Llyn Cwellyn*	120	EAW	Type 3	Y
121	35561	*Llyn Bodlyn*	-	EAW	Type 3	N

Sources: B1-Burgess *et al*. 2008; CEH-CEH; EAW-EAW; ECRC-Other ECRC projects; F86-Fritz *et al.* 1986; G1-Goldsmith *et al.* 2005; G2-Golsmith *et al*. 2009 (Anafon); G3-Goldsmith 2010 (EA); H1-Holman *et al.* 2007; HY86-Howe & Yates 1953; J1-Jehu, 1902; M1-Allott *et al.* 1994; M2-Monteith, 1995; M3-Monteith, 1996; M4-Monteith, 1997; P1-Perrow et al. 2005; P87-Patrick *et al.* 1987; S86-Stevenson *et al.* 1986; W1-Wade *et al*. in prep.

APPENDIX 2: Procedure used for digitising paper copy maps to OS xyz data.

Suitable for low density coverage of bathymetric point data, where original coordinate and depth records are absent.

Requirements: Scanned copy of map (TIFF), OS Georeferenced map tile (TFW, TIFF), ARCMAP software. Create Site/Lake specific folder in ArcCatalog

1. Open ARCMap
2. Add data - OS TIFF map (1:25000 scale recommended)
3. Open Georeference Toolbar from ARC Toolbox
4. Add TIFF of scanned map
5. Adjust transparency / layers to make all TIFFs visible
6. Using Autofit, Rotate, Scale and Shift functions, line up lake outlines to match.
7. Save ARCMap (.mxd) file.
8. Open ArcCatalog
9. New - Shapefile - Multipoint in Site Folder
10. Add Multipoint Shapefile
11. Start Editor. Add points corresponding to depths marked on paper map. OS x,y coordinates are recorded. Continue until all points recorded. Finish Sketch. Stop and Save Edits.

Converting a multipoint feature class into a point feature class:

12. Start Edit. Select Multipoint file.
13. Open Edit > Advanced Editing Toolbar
14. Select all features in Multipoint file
15. Click on Advanced Editing Toolbar 'Explode multipart feature' button.
16. Save Edits
17. Open ArcToolbox > Data Management Tools > Features > Feature To Point
18. Specify the multipoint feature class as the input feature and specify output feature class name - <dataset ID>_<WBID>_xyz.shp. Click Run.
19. Open Attribute Table for xyz shapefile. Add Field ' Depth'. Select individual depth points on map and update 'Depth' value in attribute table. Double clicking on row highlights point on map for reference.
20. Stop and Save Edits
21. A raw xyz file can be produced by opening the .dbf file in Excel and saving as a .csv file.

A bathymetric raster is produced from this data using the procedure described in Appendix 4.

APPENDIX 3: Coordinate transformation from Lowrance GPS data (WGS84) to OSGB36 using ARCMAP 9.2

1. Open Arc Map
2. Apply new layer. Open .csv text file with lon, lat, depth, index headings
3. Display xy data
4. Enter lon (x), lat (y)
5. Select - pre-defined geographic coordinates _world_wgs1984.prj – Click OK and event data heading is shown in left hand 'Layers' column
6. Events (Right Click) => Data – Export Data – 'WBID_bathypoints_wgs84.shp' Click OK.
7. Open ArcToolbox _ Data Management_Projections_Feature_Project
   Select - File: 'WBID_bathypoints_wgs84.shp'
   Select – File output 'WBID_bathypoints_osgb36.shp'
   Select – Predefined projected coordinate system
   Select – British National Grid.prj
   Select-Geographic Transformation OSGB_1936_to_WGS84 (5)
8. Right click shapefile WBID_bathypoints_osgb36.shp in left hand 'Layers' column => Open Attribute Table.
9. Add Fields to table - os_x, os_y (double type)
10. Highlight os_x column – Calculate geometry – OK. Repeat process with os_y column. Go to the directory and folder where the lake GIS data is being saved. Open the 'WBID_bathypoints_osgb36.dbf'. Do not change the file but 'Save As' a .csv file. Open the .csv file and remove columns to leave – Index, os_x, os_y and depth.

Re-name file as 'WBID_lake_name_xyz. This file provides the raw location and depth data for subsequent bathymetric map production.

APPENDIX 4: Protocol describing production of lake depth models from bathymetric soundings using

This appendix describes the process of using the ArcGIS Inverse Distance Weighted (IDW) Interpolation method and compares it with the Spline Interpolation method.

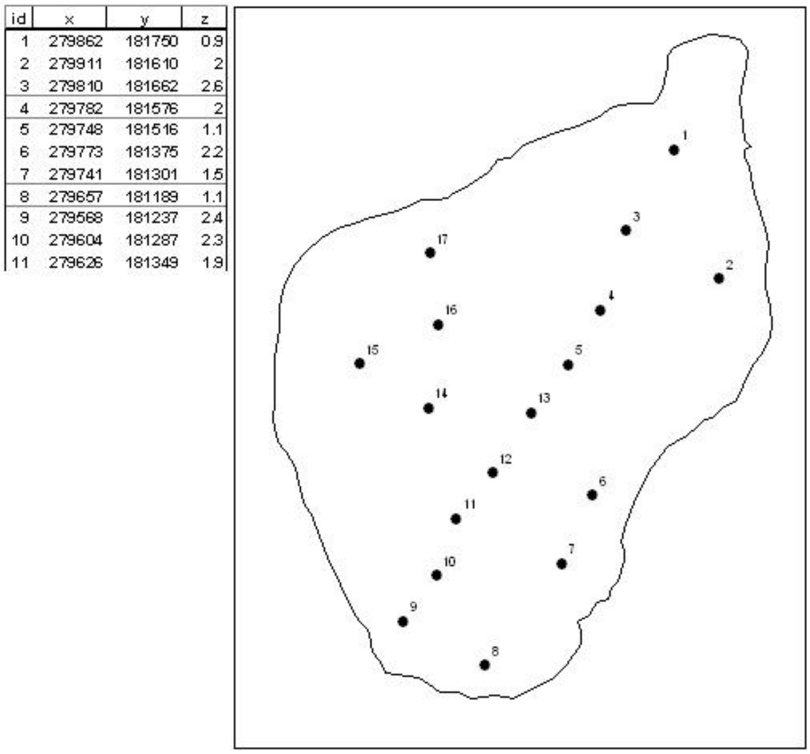
Appendix 4.1 Data preparation

Required:

i) a comma-delimited text file with x,y,z values using OS cords (OSGB36) (see Appendix 3 for conversion of WGS84 coordinates to OSGB36).

ii) a line layer (not a polygon) for lake outline, could be from UKLakes or digitised from OS 1:10,000 raster map for example. Coordinate system for line should be OSGB36.

Add the above data to a new map in ArcMap. Make a point shapefile from the x,y,z data.



id	x	y	z
1	279862	181750	0.9
2	279911	181610	2
3	279810	181662	2.6
4	279782	181576	2
5	279748	181516	1.1
6	279773	181375	2.2
7	279741	181301	1.5
8	279657	181189	1.1
9	279568	181237	2.4
10	279604	181287	2.3
11	279626	181349	1.9

Figure A4.1 Kenfig Pool (WBID – 42170) depth data gathered by hand, using hand-held echo sounder (Monteith et al. 1996).

The inset in Figure A4.1 shows the contents of the xyz data file. The bathymetric map from Monteith et al. (1996) has been scanned, re-digitised and sample points georeferenced by overlaying the image on a 1:10000 OS raster (Appendix 2).

Note that where data do not extend to the lake edge, the described methods can be enhanced by adding ‘pseudo’ data points to the point shape file with depth values for the lake edge (could be 0m or known altitude of lake surface on day of survey). No extra points have been added during this work.

Appendix 4.2 IDW (Inverse Distance Weighted) Interpolation

We used the IDW method in Spatial Analyst for ArcGIS. From the Spatial Analyst menu select *Interpolate to Raster* > *Inverse Distance Weighted*.

Input points: select the shape file containing the bathymetric soundings.

Z value field: select the field which contains depths.

Power: 2 is the recommended value and the default, a higher number gives more weighting to the nearest points.

Search radius type: determines how the interpolation process will select data points to compute the grid cell values. Variable or fixed are the options. Variable is recommended, select a number of points between 5 and 12 (higher number results in more 'smoothing') and set a maximum distance if you wish to prevent the model from extrapolating too far. For example, setting this distance to 100m will prevent a value being modelled for a cell where there is no data point within a 100m radius. As a guide, set the number of points to 9 and the maximum distance to a value approximately 2x the average data point spacing.

Use barrier polylines: select the shape file containing lake outline (must be a line feature).

Output cell size: The selection of a reasonable output cell size is somewhat subjective. The cell size should not be so large that one cell covers more than 1 data point, but not so small that the resulting grid will be unwieldy and unrealistically detailed. *As a guide choose a cell size between 20% and 50% of the average data point spacing*. So, if the average spacing between points is 100m, choose a cell size between 10m and 50m.

Output raster: select a name and location for the resulting grid.

The IDW process will compute a raster of grid cells which is then displayed (see Figure A4.2).

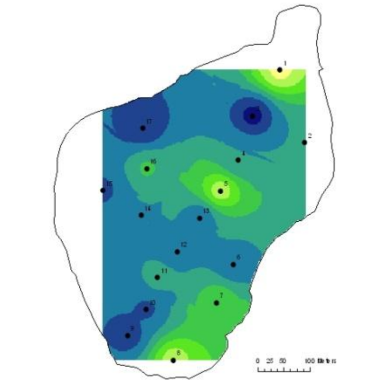
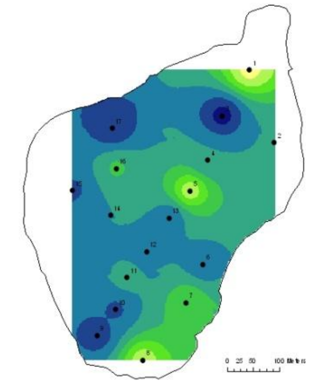
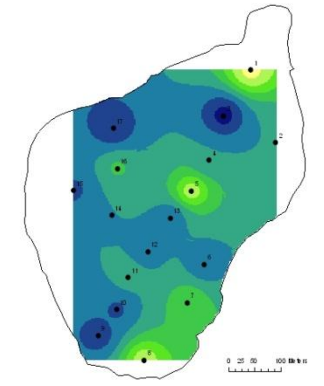
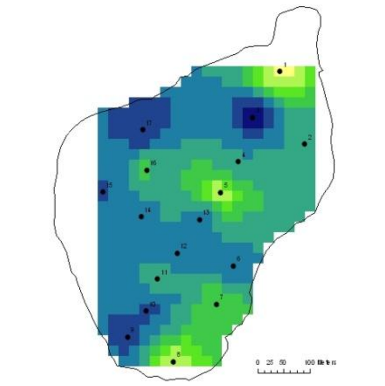
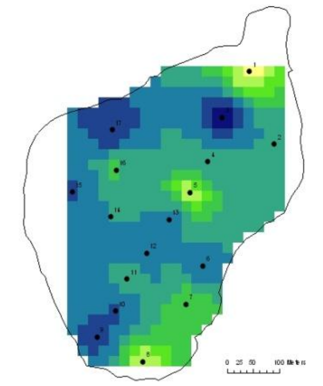
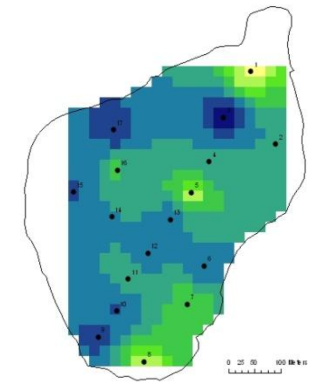
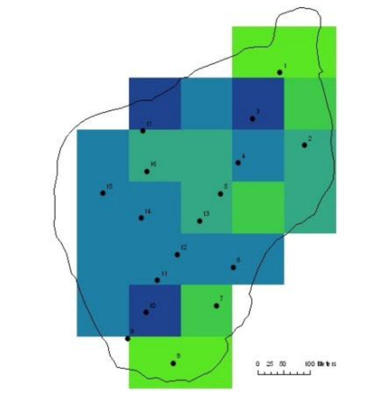
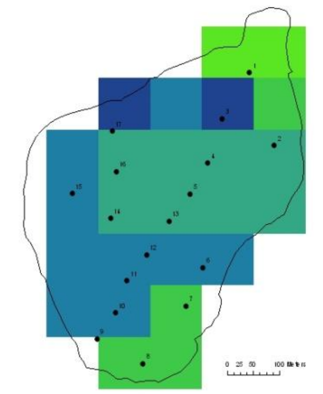
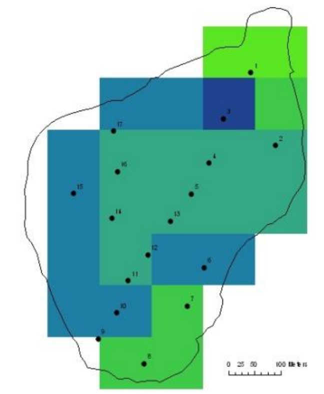
Cell size	5 points	8 points	12 points
2m			
20m			
100m			

Figure A4.2 Examples shown for different IDW settings (3 different cell sizes and 3 different numbers of points for Kenfig Pool data. All other settings are default.

It should be immediately obvious that the 2m grid cell size is too fine given the spacing of the points (average spacing is about 90m). With 5 points there are some artefacts being introduced by the interpolation process, 12 points gives a smoother output. Conversely, the 100m cell size is too coarse and will not be able to represent the spatial variation in depth in the given area. The 20m cell size appears to be the most suitable. Given the scarcity of points, a smaller number of points should be used, 5 is probably the best option here.

Appendix 4.3 SPLINE Interpolation

Like IDW, Spline interpolation creates a grid of regular-sized square cells and a modelled depth for each cell. Spline interpolation differs from IDW in that it minimizes the total curvature of the modelled surface.

This method is best for subtle variations in surface values such as elevation, water table heights, or pollution concentrations. Also, it is not possible to constrain the interpolation to the boundaries of the lake using the standard Spline tool. If there are large changes in the surface within a short horizontal distance, the spline algorithm can overshoot estimated values.We consider therefore the IDW method more practicable for this CCW work.

To perform the Spline method you will need Spatial Analyst for ArcGIS. From the Spatial Analyst menu select *Interpolate to Raster* > *Spline*.

Input points: select the shape file containing the bathymetric soundings.

Z value field: select the field which contains depths.

Spline type: two types are available - Regularized or Tension. The Regularized method creates a smooth, gradually changing surface with values that may lie outside the sample data range. The Tension method controls the stiffness of the surface according to the character of the modeled phenomenon. It creates a less smooth surface with values more closely constrained by the sample data range. For bathymetric data the Tension method is most appropriate.

Weight: For the Tension Spline method, the weight parameter defines the weight of tension. The higher the weight, the coarser the output surface. The values entered must be equal to or greater than zero. The typical values are 0, 1, 5, and 10.

Number of points: Number of points identifies the number of points used in the calculation of each interpolated cell. The more input points you specify, the more each cell is influenced by distant points and the smoother the output surface. The larger the number of points, the longer it will take to process the output raster.

Output cell size: The selection of a reasonable output cell size is somewhat subjective. The cell size should not be so large that one cell covers more than 1 data point, but not so small that the resulting grid will be unwieldy and unrealistically detailed. As a guide choose a cell size between 20% and 50% of the average data point spacing. So, if the average spacing between points is 100m, choose a cell size between 10m and 50m.

Output raster: select a name and location for the resulting grid (example shown Figure A4.3).

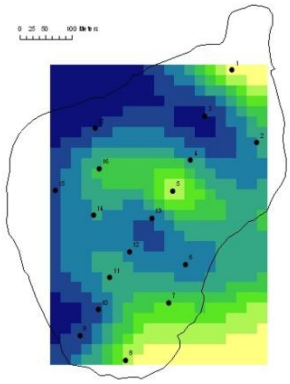
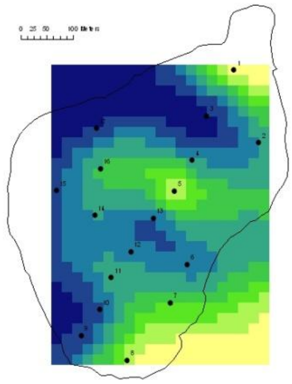
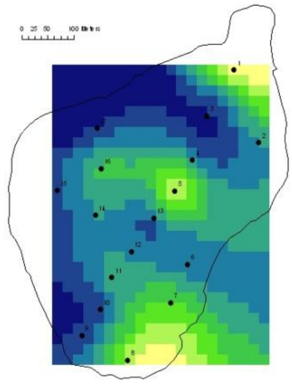
Cell size	5 points	8 points	12 points
20m			

Figure A4.3 Example output from the Spline method using weight of 0.1. Note that the grids would need clipping with the boundary of the lake. A ‘Spline with Barriers’ script is available for ArcGIS to constrain the grid within the lake outline.

Comments: With a cell size of 20m, it can be seen that changing the number of points has quite a significant effect on the output.

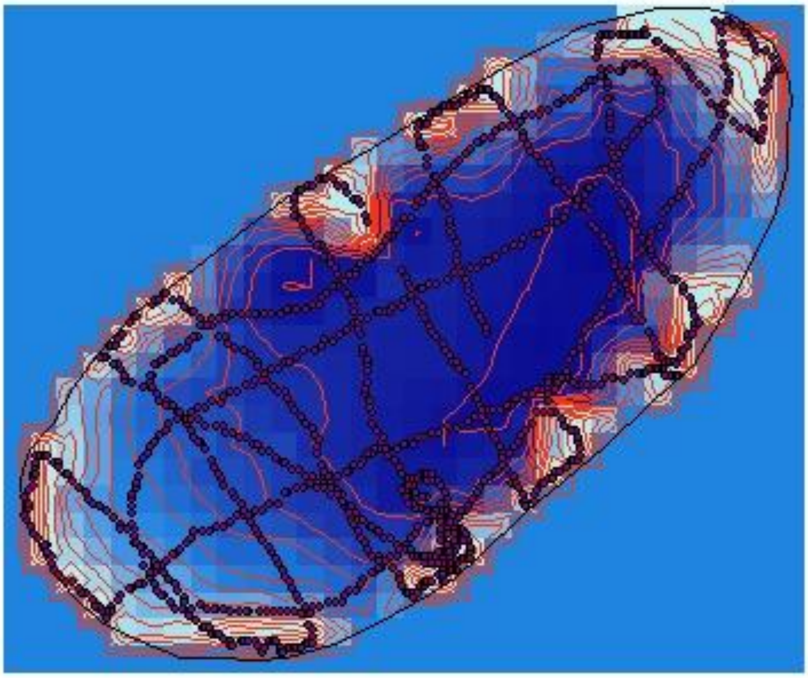
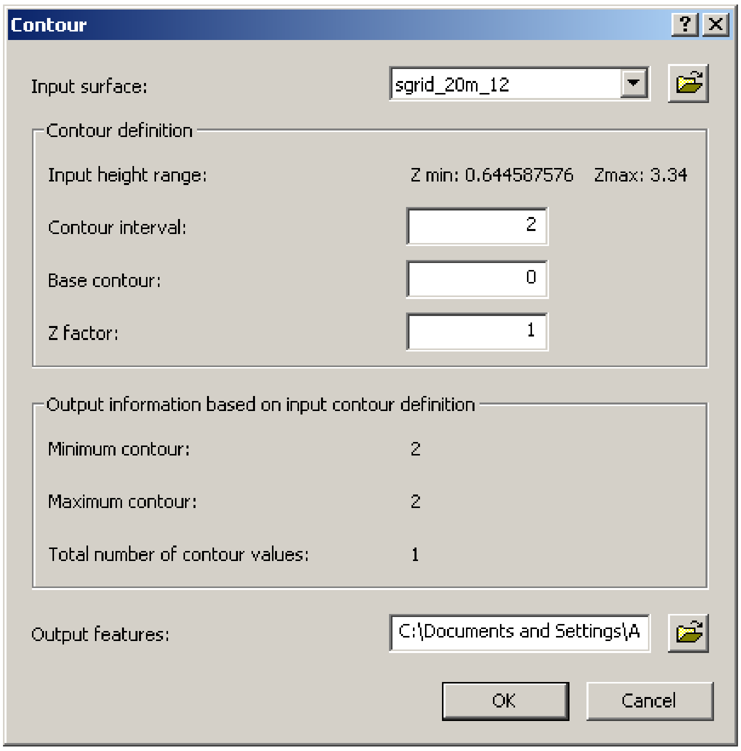


Figure A4.4 Example bathymetric surface of Llyn Cadarn using ‘Spline with Barriers’ script in ArcGIS. The output interpolates across the bounding rectangle, though the lake outline is clearly a boundary.

Appendix 4.4 Computing Contours

Contours can be created from grids in ArcGIS using the Spatial Analyst extension. From the Spatial Analyst menu select *Surface Analysis* > *Contour* (Figure A4.5 below).



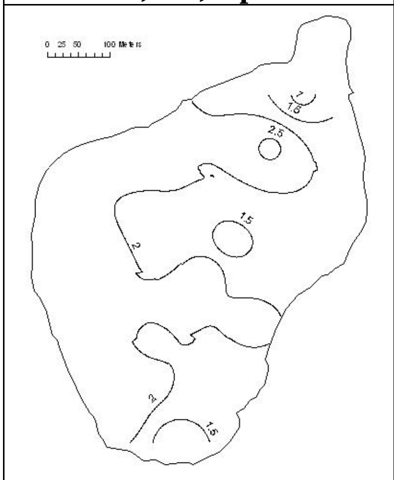
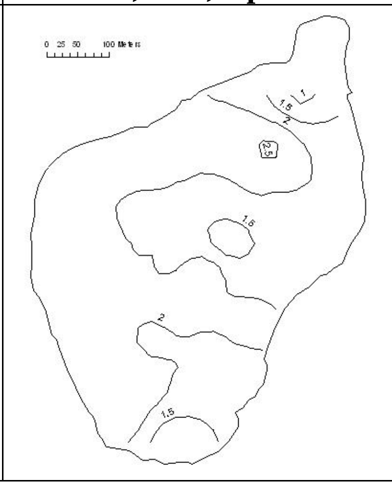
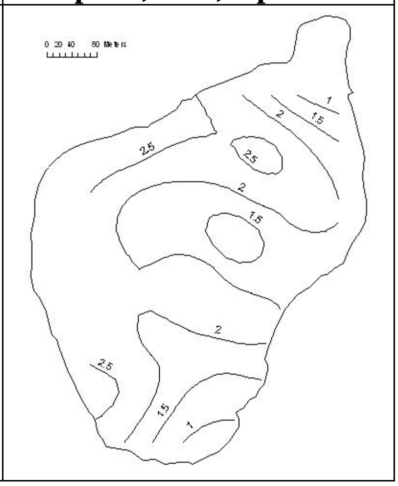
IDW, 2m, 5 points	IDW, 20m, 5 points	Spline, 20m, 5 points
		

Figure A4.5 Settings panel in ARC GIS for contours and contours produced for Kenfig Pool. This shows that contours vary greatly depending on the method and parameters used during the interpolation process.

Appendix 4.5 Computing Bathymetric Statistics – ArcGIS/Map

Bathymetric statistics such as total volume and area of lake for a given depth range, can be computed easily using the grids produced in Section 2 and tools in ArcGIS. Requirement: 3D Analysts and Spatial Analyst extensions enabled.

Open a grid and in the 3D Analyst menu select *Surface Analysis* > *Area and Volume*. The dialog box allows the user to compute statistics above or below a plane. These data can be appended to a text file.

Appendix 4.6 Exporting Raster Data

Once a suitable grid has been produced the data may also be exported as an ASCII file for use in other programs (e.g. MS Excel, MS Access). In Arc ToolBox use the *Raster to ASCII* dialog.

The ASCII file (Figure A4.6 below) contains 6 header lines followed by lines of data, one line per row of data organised spatially so that the first value of the first line of data is the top left cell value including NODATA cells, i.e. where interpolation did not occur.

```
ncols        21

nrows        29

xllcorner    279510.24351288

yllcorner    181179.42816462

cellsize     20

NODATA_value  -9999

-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 2.018974 1.97747 1.951749 1.876381 1.760072 1.573091
1.275486 1.019523 0.9008538 0.9696012 1.129701 1.289136

-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 2.095775 2.063014 2.035513 2.033525 1.993008 1.92276
1.728078 1.490065 1.193305 1.034871 1.088536 1.237887 1.383103

-9999 -9999 -9999 -9999 -9999 -9999 2.225898 2.170163 2.130331 2.102392 2.090348 2.117829 2.124803
2.129626 2.041898 1.890047 1.620233 1.416362 1.383485 1.451051 1.536778

-9999 -9999 -9999 2.369124 2.376903 2.361488 2.253937 2.203037 2.169679 2.131159 2.132109 2.105115
2.239022 2.270199 2.36104 2.305967 2.06518 1.818313 1.700225 1.684376 1.706347

2.208163 2.258791 2.349021 2.398752 2.414502 2.398921 2.282508 2.203552 2.151385 2.136663 2.163048
2.129646 2.21087 2.388836 2.554138 2.540705 2.303165 2.045139 1.902184 1.856076 1.846078

2.202781 2.260416 2.345974 2.440557 2.480433 2.422364 2.292437 2.184978 2.116523 2.091543 2.109897
2.103803 2.181585 2.357248 2.524091 2.514173 2.314071 2.100578 1.982856 1.949121 1.93731

2.226015 2.26522 2.314233 2.430315 2.483162 2.400108 2.231973 2.130491 2.059538 2.028473 2.036138
2.078626 2.078378 2.188404 2.295657 2.302153 2.194707 2.066615 1.996565 1.9875
etc …
```

Figure A4.6 Example of ASCII file output

Exported into a spreadsheet and knowing the cell size of the grid used, some simple calculations can generate the volume and depth data. This process can be speeded up by using R software.

Note that the grids produced by the IDW and Spline process and the exported ASCII data have arbitrary origins as seen in the xllcorner and yllcorner values.

Appendix 5: Details of raster surfaces generated for CCW Lakes

KEY

B-Bathy ID no.; D-Dataset ID no.; IDW Method - IDW Variable or Fixed; Radius – maximum distance of points used in IDW; Neighbours – minimum number points used in IDW, 0 indicates use of maximum number of points available.

Table A5.1 Details of raster surfaces generated for CCW lakes

B	D	WBID	IDW Method	Resolution Cell size (m)	Radius (m)	Neighbours (n)	File name
100	3	32746	IDW Variable	10	80	12	**b100_32746**
101	4	33160	IDW Variable	10	100	12	**b101_33160**
102	5	33631	IDW Variable	2	25	12	**b102_33631**
103	6	33864	IDW Variable	2	30	12	**b103_33864**
104	7	34813	IDW Variable	2	20	12	**b104_34813**
105	8	37168	IDW Variable	4	40	12	**b105_37168**
106	9	37617	IDW Variable	5	30	12	**b106_37617**
107	10	38321	IDW Variable	5	40	12	**b107_38321**
108	11	38544	IDW Variable	10	80	12	**b108_38544**
109	12	39267	IDW Variable	5	30	12	**b109_39267**
110	13	39796	IDW Variable	5	30	12	**b110_39796**
111	14	39813	IDW Variable	10	40	12	**b111_39813**
112	15	40338	IDW Variable	2	20	12	**b112_40338**
113	16	41973	IDW Variable	5	20	12	**b113_41973**
114	17	42721	IDW Variable	5	50	12	**b114_42721**
115	18	36535	IDW Variable	5	30	12	**b115_36535**
116	20	33843	IDW Variable	2	0	12	**b116_33843**
117	118	34987	IDW Fixed	40	500	0	**b117_34987**
118	119	34864	IDW Fixed	10	70	0	**b118_34864**
119	22	34243	IDW Fixed	5	50	0	**b119_34243**
120	120	34002	IDW Variable	60	1000	0	**b120_34002**
121	23	34319	IDW Fixed	2	40	0	**b121_34319**
122	21	33962	IDW Fixed	5	60	0	**b122_33962**
123	19	33730	IDW Fixed	10	100	0	**b123_33730**
124	24	34633	IDW Fixed	4	60	0	**b124_34633**
125	26	35650	IDW Variable	2	50	12	**b125_35650**
126	28	34044	IDW Variable	1	0	12	**b126_34044**
127	29	37437	IDW Variable	4	60	12	**b127_37437**
128	30	37834	IDW Fixed	4	40	0	**b128_37834**
129	31	38394	IDW Variable	2	20	12	**b129_38394**
130	32	38422	IDW Fixed	2	40	0	**b130_38422**
131	25	35426	IDW Variable	5	30	12	**b131_35426**
132	60	33862	IDW Variable	2	30	12	**b132_33862**
133	61	34153	IDW Variable	4	150	12	**b133_34153**
134	62	35439	IDW Variable	2	30	12	**b134_35439**
135	38	33836	IDW Variable	10	50	12	**b135_33836**
136	27	37080	IDW Variable	5	60	12	**b136_37080**
137	63	41602	IDW Variable	10	80	12	**b137_41602**
138	106	32640	IDW Variable	2	30	12	**b138_32640**
139	110	34821	IDW Variable	2	50	12	**b139_34821**
140	111	34916	IDW Variable	2	30	12	**b140_34916**
141	113	35834	IDW Variable	2	30	12	**b141_35834**
142	116	38856	IDW Variable	5	50	12	**b142_38856**
143	117	39890	IDW Variable	5	50	12	**b143_39890**
144	36	33374	IDW Variable	10	60	12	**b144_33374**
145	35	32792	IDW Variable	2	40	12	**b145_32792**
146	40	34051	IDW Variable	5	50	12	**b146_34051**
147	39	33974	IDW Variable	10	80	12	**b147_33974**

B	D	WBID	IDW Method	Resolution Cell size (m)	Radius (m)	Neighbours (n)	File name
148	42	34632	IDW Variable	5	50	12	**b148_34632**
149	43	34845	IDW Variable	5	40	12	**b149_34845**
150	47	35056	IDW Variable	10	35	12	**b150_35056**
151	49	35233	IDW Variable	5	50	12	**b151_35233**
152	52	36177	IDW Variable	2	35	12	**b152_36177**
153	55	38240	IDW Fixed	10	65	0	**b153_38240**
154	50	35444	IDW Variable	2	30	12	**b154_35444**
155	74	32948	IDW Variable	50	200	9	**b155_32948**
156	75	32968	IDW Variable	20	150	12	**b156_32968**
157	76	33337	IDW Variable	20	0	12	**b157_33337**
158	91	40297	IDW Variable	20	100	12	**b158_40297**
159	92	40571	IDW Variable	20	150	5	**b159_40571**
160	94	42170	IDW Variable	20	0	5	**b160_42170**
161	86	38623	IDW Variable	5	0	8	**b161_38623**
162	96	33627	IDW Variable	10	0	5	**b162_33627**
163	100	34622	IDW Variable	10	150	5	**b163_34622**
164	101	34780	IDW Variable	10	0	12	**b164_34780**
165	44	34854	IDW Variable	5	100	12	**b165_34854**
166	45	34895	IDW Variable	4	50	12	**b166_34895**
167	46	34928	IDW Variable	4	40	12	**b167_34928**
168	48	35180	IDW Variable	5	30	12	**b168_35180**
169	51	36159	IDW Fixed	5	50	0	**b169_36159**
170	53	36267	IDW Variable	4	30	12	**b170_36267**
171	54	38163	IDW Variable	4	30	12	**b171_38163**
172	56	38282	IDW Fixed	4	40	0	**b172_38282**
173	57	38525	IDW Variable	5	50	12	**b173_38525**
174	59	33374	IDW Fixed	5	40	0	**b174_33374**
175	105	39154	IDW Variable	5	100	12	**b175_39154**

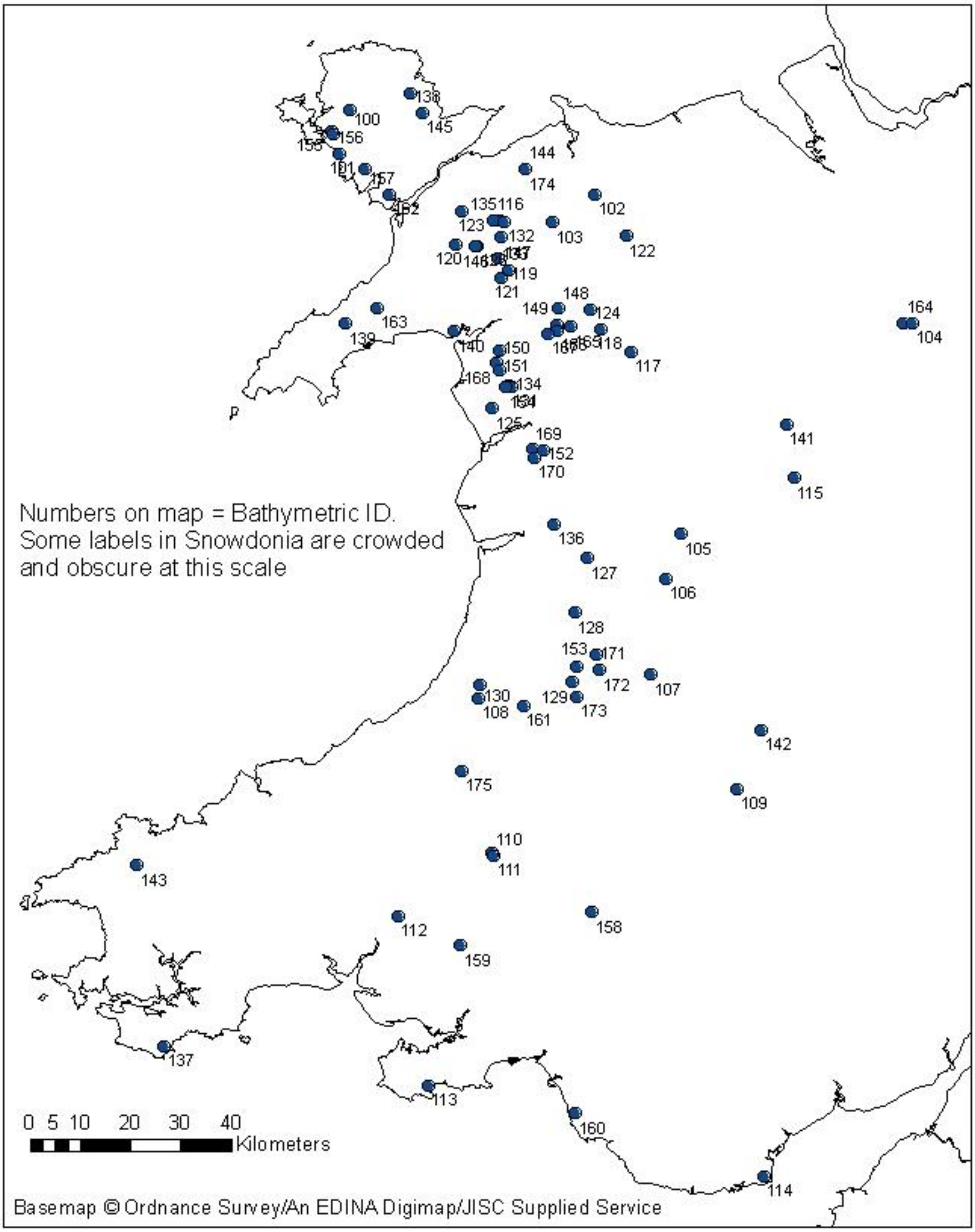


Figure A5.1 Basic map showing locations of generated bathymetric grid files in Wales. From Final Data 16-07-2010.

Appendix 6: R: Script used to process compiled CCW bathymetric data and interpolated raster grids.

The R: script can be found in the _docs folder in the Final Data folder

Outputs

- Summary diagram of lake and 0.5m depth intervals
- Total Volume (m^3), Area (m^2), mean depth (m) and max depth (m)
- Graphs of Area/Depth and Volume/Depth
- Text file (.csv) of volume/area values at 0.5 m depth intervals.
- Single shapefile of all 0.5m depth interval polygon coverage
- Individual shapefiles of 0.5m depth interval polygons

```
########################################################################
## Script to process compiled bathymetric data and interpolated      ##
## grids                                                             ##
##                                                                   ##
## Author: Gavin L. Simpson                                          ##
## Copyright: Ensis Ltd. 2011                                        ##
##                                                                   ##
## Version 1                                                         ##
##                                                                   ##
## This work is licenced under a Creative Commons By Attribution 3.0 ##
## licence. Details of the licence are located here:                 ##
##                                                                   ##
## http://creativecommons.org/licenses/by/3.0/                       ##
##                                                                   ##
## Please cite as:                                                   ##
##                                                                   ##
## Simpson G.L. (unpublished R code)                                 ##
##                                                                   ##
## To run this yourself, you will need R 2.11-1 installed            ##
## and also have installed the maptools package and any of it's      ##
## dependencies.                                                     ##
##                                                                   ##
## This script was generated on Linux as such there are several      ##
## locations in the code that reference locations on a Linux         ##
## Filesystem. Substitute your own file/folder locations as          ##
## required.                                                         ##
########################################################################

## data are in ../../data/CCW_Final_Data,
## EDIT for your file/folder location where the bathymetric data can
## be found.
flist <- list.files("~/work/projects/ccw/data/CCW_Final_Data")
n.bathy <- length(flist)

## Load maptools package - readAsciiGrid()
require(maptools)
require(rgdal)

## volume function
volFun <- function(x, cellarea) {x * cellarea}

## object to hold the summary morphometric output
## we'll fill this in as we go through the loop
morpho <- data.frame(matrix(NA, nrow = n.bathy, ncol = 6))
names(morpho) <- c("BathyID","WBID","Mean","Max","Area","Vol")
```

```
## penalise scientific notation
opts <- options("scipen" = 3)

## loop over the list of files and process
system.time({
for(i in seq_along(flist)) {
    ## get the ascii grid filename - EDIT initial dir path
    f <- list.files(paste("~/work/projects/ccw/data/CCW_Final_Data/",
                          flist[i], "/", sep = ""),
                    pattern = ".asc")

    ## Check if results DIR exists, if not, create it
    ## EDIT this relative link to match your filesystem
    res.dir <- paste("../results/", flist[i], sep = "")
    if(!file.exists(res.dir)) {
        dir.create(res.dir)
    }
    ## check the asc file exists; if not next i
    if(isTRUE(all.equal(length(f), 0))) {
        next
    }

    ## load ASCII grid
    ## EDIT this path to match your fielsystem
    g <- readAsciiGrid(paste("~/work/projects/ccw/data/CCW_Final_Data/",
                             flist[i], "/", f, sep = ""),
                       proj4string = CRS("+init=epsg:27700"))

    ## Compute a common filename for everything - just add extension
    ## or additional info
    ## EDIT - again edit this relative link to match your filesystem
    fname <- paste("../results/", flist[i], "/", sub(".asc", "", f), sep =
"")

    ## now easy to compute stats on the object
    cellsize <- gridparameters(g)$cellsize
    ## Mean depth
    mean.depth <- mean(g@data, na.rm = TRUE)
    ## Max interpolated depth
    max.depth <- max(g@data, na.rm = TRUE)
    ## Total volume
    total.vol <- sum(prod(cellsize) * g@data, na.rm = TRUE)
    ## Area - count number of non-missing, multiply by prod(cell sizes)
    total.area <- sum(!is.na(g@data)) * prod(cellsize)
    ## hypsographic curve
    ## 1) get seq of 0.5m intervals
    interval <- 0.5
    dseq <- seq(0, max.depth+0.5, by = interval)
    ## 2) split data into these chunks
    cuts <- cut(g@data[,1], dseq)
    ## 3) Cumulative area of 0.5 m interval slices through lake
    cumArea <- cumsum(rev(as.numeric(table(cuts)))) * prod(cellsize)

    ## Hypsographic curve
    pdf(paste(fname, "_hypsographic_curve_.pdf", sep = ""),
        height = 8, width = 8, paper = "special", version = "1.4",
        onefile = FALSE)
    plot.depths <- rev(dseq[-1] - (interval / 2))
    plot(plot.depths ~ cumArea, type = "b", ylim = rev(range(dseq)),
         ylab = "Depth (m.)", xlab = expression(Area ~ (m^2)))
    axis(side = 3, at = seq(0, 1, by = 0.2) * total.area,
         labels = seq(0, 100, by = 20))
    mtext("Percent Area", side = 3, line = 2.5)
```

```
grid()
box()
dev.off()

## Depth - Volume curve
## 1) split data according to cuts
splt.dat <- split(g@data[,1], cuts)
## 2) Apply volume functions
splt.vol <- lapply(splt.dat, volFun, prod(cellsize))
## 3) sum volume in each depth category
sum.vol <- sapply(splt.vol, sum, na.rm = TRUE)
## 4) cumulative volume
cumVol <- cumsum(sum.vol)

## plot depth - volume curve
pdf(paste(fname, "_depth_-_volume_curve.pdf", sep = ""),
    height = 8, width = 8, paper = "special", version = "1.4",
    onefile = FALSE)
plot.depths <- dseq[-1] - (interval / 2)
plot(plot.depths ~ cumVol, type = "b", ylim = rev(range(dseq)),
     ylab = "Depth (m.)", xlab = expression(Volume ~ (m^3)))
axis(side = 3, at = seq(0, 1, by = 0.2) * total.vol,
     labels = seq(0, 100, by = 20))
mtext("Percent Volume", side = 3, line = 2.5)
grid()
box()
dev.off()

## write out the data for the curves
write.csv(cbind(Volume = cumVol, Area = rev(cumArea)),
          file = paste(fname, "_curve_data.csv"))

## ASCII grid filename contains bathy ID and WBID
## [[1]] of ids == bathyID, [[2]] of ids == WBID
ids <- strsplit(sub(".asc", "", f), "_")

## insert the morpho data for this lake in the morpho object
morpho[i,] <- c(ids[[1]][1], ids[[1]][2], mean.depth, max.depth,
                total.area, total.vol)

## Put together a base graphics layout of the curves plus the bathy
pdf(paste(fname, "_composite_display.pdf", sep = ""),
    height = 9, width = 8, paper = "a4", version = "1.4",
    onefile = FALSE, pointsize = 12)
layout(matrix(c(1,4,2,3), ncol = 2, byrow = TRUE))
## oma for page number at bottom
par(oma = c(1,0,3,0))
op <- par(mar = c(2,2,0,2) + 0.1)
## compute the number of colours for the plot, if more than 13x3
## compute 13x3 new ones spread nicely across interval
if(length(dseq) > (13*3)) {
    breaks <- round(seq(dseq[1], dseq[length(dseq)],
                        length.out = 13*3), 1)
    legDepths <- breaks
} else {
    breaks <- dseq
    legDepths <- seq(0, ceiling(max.depth), by = interval)
}
## plotting colours
cols <- bpy.colors(length(breaks)-1)
## hmm.... why suppressWarnings? breaks being passed on...
suppressWarnings(image(g, col = cols, breaks = breaks))
grid()
## Don't plot scale bar as sites vary too widely in size...
```

```
#usr <- par("usr")
#usr.d <- c(abs(diff(range(usr[c(1L, 2L)]))),
#           abs(diff(range(usr[c(3L, 4L)]))))
#SpatialPolygonsRescale(layout.scale.bar(height = 0.05),
#                        offset = c(usr[1L], usr[3L]),
#                        scale = 100,
#                        fill = c("transparent","black"),
#                        plot.grid = FALSE)
title(sub = bquote(Volume == .(round(total.vol, 2)) ~ m^3 ~~~
      Area == .(round(total.area, 2)) ~ m^2), line = 1)
## expression(paste(paste("Volume:", round(total.vol, 2), "m^3"),
## paste("Area:", total.area, "m^2"), sep = "    ")),
## line = 1)
par(op)
## Hypsographic curve
plot.depths <- rev(dseq[-1] - (interval / 2))
plot(plot.depths ~ cumArea, type = "b", ylim = rev(range(dseq)),
     ylab = "Depth (m.)", xlab = expression(Area ~ (m^2)),
     cex = 0.8)
axis(side = 3, at = seq(0, 1, by = 0.2) * total.area,
     labels = seq(0, 100, by = 20))
mtext("Percent Area", side = 3, line = 2.5, cex = 0.8)
grid()
box()
## plot depth - volume curve
plot.depths <- dseq[-1] - (interval / 2)
plot(plot.depths ~ cumVol, type = "b", ylim = rev(range(dseq)),
     ylab = "Depth (m.)", xlab = expression(Volume ~ (m^3)),
     cex = 0.8)
axis(side = 3, at = seq(0, 1, by = 0.2) * total.vol,
     labels = seq(0, 100, by = 20))
mtext("Percent Volume", side = 3, line = 2.5, cex = 0.8)
grid()
box()
#print(par("cex.lab"))
## Spare Panel
op <- par(mar = c(3,1,1,1) + 0.1)
plot(1:10, type = "n", axes = FALSE, ann = FALSE)
legend("center", fill = cols, border = cols,
       legend = paste(legDepths[-length(legDepths)], legDepths[-1],
       sep = " - "),
       bty = "n", ncol = 3, title = "Depth (m.)")
title(sub = bquote(Mean~Depth == .(round(mean.depth, 2)) ~ m ~~~
      Maximum~Depth == .(round(max.depth, 2)) ~ m), line = 2)
## Extra titles etc
lake.name <- strsplit(flist[i], "_")[[1]]
lake.name <- paste(lake.name[2:length(lake.name)], collapse = " ")
title(main = paste(lake.name, " (ID: ", ids[[1]][1], "   WBID: ",
      ids[[1]][2], ")", sep = ""),
      outer = TRUE, cex.main = 1.5, line = 1.5)
title(main = paste("(Generated from ASCII grid ", f, " on ",
      strftime(Sys.Date(), format = "%d %b %Y"), ")", sep = ""),
      font.main = 1, cex.main = 0.9, line = 0.5, outer = TRUE)
layout(1)
## reset plotting
par(oma = c(0,0,0,0), mar = c(5,4,4,2) + 0.1)
dev.off()

## Next step is to process the shapefiles for each layer
## and save them in the shapefiles sub folder
##
## Check if shapefile DIR exists, if not, create it
## EDIT this relative link to match your filesystem
shp.dir <- paste("../results/", flist[i], "/shapefiles/", sep = "")
```

```
    if(!file.exists(shp.dir)) {
        dir.create(shp.dir)
    }
    ## Convert grid 'g' to a spatial pixels object
    g.spix <- as(g, "SpatialPixelsDataFrame")
    ## Convert 'g.spix' to a spatial polygons data frame
    g.spdf <- as(g.spix, "SpatialPolygonsDataFrame")
    ## index references the non missing grid cells by 0.5m interval
    cuts.na <- is.na(cuts)
    idx <- as.numeric(cuts)[!cuts.na]
    ## allow use of the non-free GPClib
    gpclibPermit()
    ## union the spatial polygons data frame by depth interval
    ## Slow (!) for large grids (i.e. large number of polygons/pixels)
    g.union <- unionSpatialPolygons(g.spdf,
                                    factor(levels(cuts[!cuts.na])[idx],
                                           levels = levels(cuts[!cuts.na])))
    ## data frame needed for the shapefile creation
    ## cuts can for some reason have a level but 0 entries
    ## so we need to drop this one
    CUTS <- levels(cuts)[table(cuts[!cuts.na]) != 0]
    dat.g <- data.frame(DepthInterval = CUTS)
    rownames(dat.g) <- CUTS
    ## Write this full object out as a shapefile
    writeOGR(SpatialPolygonsDataFrame(g.union, data = dat.g), dsn = ".",
             layer = paste(shp.dir, flist[i], "_all_depths", sep = ""),
             driver = "ESRI Shapefile")
    ## loop to produce the individual depth interval polygons
    ## and write each of the M polygons out in a shapefile
    for(j in seq_along(slot(g.union, "polygons"))) {
        layerName <- paste(shp.dir, flist[i], "_", CUTS[j], sep = "")
        shpPoly <- SpatialPolygons(slot(g.union, "polygons")[j],
                                   proj4string = CRS("+init=epsg:27700"))
        shpTemp <- SpatialPolygonsDataFrame(shpPoly,
                                            data = dat.g[j, , drop = FALSE])
        writeOGR(shpTemp, dsn = ".", layer = layerName,
                 driver = "ESRI Shapefile")
    }
}
})

## write out the morpho object into ../results
## EDIT this relative link to match your filesystem
write.csv(morpho, "../results/morphometric_data_summary.csv",
          row.names = FALSE)

## reset the options
options(opts)
```

Appendix 7: Morphometric statistics of bathymetries. Results of output from R processing of raster grid data.

Table A7.1 Morphometric statistics of bathymetries. Results of output from R: processing of raster grid data.

Bathy_ID	Dataset_ID	WBID	Ref.	mean depth	max depth	Area (m^2)	Volume (m^3)
100	3	32746	B1	0.84	1.62	234700	196713.5
101	4	33160	B1	1.56	2.44	236400	368811.3
102	5	33631	B1	2.31	4.28	16352	37717.7
103	6	33864	B1	1.44	7.84	15528	22403.2
104	7	34813	B1	1.28	1.70	9372	11988.4
105	8	37168	B1	2.02	5.97	67680	136881.1
106	9	37617	B1	4.00	8.00	114800	458707.7
107	10	38321	B1	4.10	7.88	30325	124283.7
108	11	38544	B1	3.37	8.31	46700	157434.3
109	12	39267	B1	3.18	8.33	103400	328635.5
110	13	39796	B1	1.54	4.44	67425	104032.5
111	14	39813	B1	1.65	4.28	59800	98404.1
112	15	40338	B1	1.57	4.40	23888	37537.8
113	16	41973	B1	1.31	1.55	16700	21848.3
114	17	42721	B1	5.37	9.99	113825	611695.8
115	18	36535	B1	0.63	0.80	12600	7977.6
116	20	33843	ECRC	2.54	6.47	5484	13906.2
117	118	34987	CEH	25.71	39.94	3599100	92542506.6
118	119	34864	CEH	21.31	34.95	333100	7098650.2
119	22	34243	ECRC	6.84	18.33	58400	399360.5
120	120	34002	EAW	25.90	36.88	842400	21818085.8
121	23	34319	ECRC	4.80	12.47	52568	252322.2
122	21	33962	ECRC	6.86	14.95	262650	1801095.6
123	19	33730	ECRC	15.89	26.92	959600	15250864.9
124	24	34633	ECRC	7.35	19.82	123344	906450.4
125	26	35650	ECRC	2.53	8.83	92076	232564.6
126	28	34044	ECRC	2.45	5.77	5124	12567.8
127	29	37437	ECRC	1.45	2.74	90176	130991.1
128	30	37834	ECRC	2.87	8.80	57776	165544.1
129	31	38394	ECRC	2.76	8.07	52644	145372.0
130	32	38422	ECRC	2.30	7.30	109740	252301.6
131	25	35426	ECRC	12.22	34.82	53175	649934.9
132	60	33862	G3	2.63	6.80	42960	113124.9
133	61	34153	G3	7.05	16.69	431136	3040163.2
134	62	35439	G3	1.67	7.84	26364	44091.6
135	38	33836	G1	3.25	9.33	107700	349608.5
136	27	37080	ECRC	1.18	2.83	27600	32454.9
137	63	41602	H1	2.07	3.09	303400	628619.6
138	106	32640	W1	0.94	1.83	9416	8853.8
139	110	34821	W1	1.18	1.78	4076	4809.1
140	111	34916	W1	1.30	1.71	11392	14822.9
141	113	35834	W1	1.31	2.40	21900	28682.8
142	116	38856	W1	0.77	2.05	26075	20020.4
143	117	39890	W1	4.45	8.75	53950	239968.6
144	36	33374	ECRC	2.01	9.06	46000	92363.1
145	35	32792	G1	4.56	6.69	10624	48478.9
146	40	34051	G1	0.55	1.43	11250	6160.4
147	39	33974	G1	2.69	10.75	88200	237544.1
148	42	34632	G1	1.60	2.33	33850	54186.2
149	43	34845	G1	1.12	5.74	32400	36372.0
150	47	35056	G1	3.80	13.46	105400	400433.3
151	49	35233	G1	1.47	7.40	28700	42298.2
152	52	36177	G1	1.27	2.11	6148	7825.3

Bathy_ID	Dataset_ID	WBID	Ref.	mean depth	max depth	Area (m^2)	Volume (m^3)
153	55	38240	G1	6.04	12.75	144900	874747.2
154	50	35444	G1	0.98	2.20	9844	9652.0
155	74	32948	M1	1.25	1.43	65000	81216.9
156	75	32968	M1	2.24	2.99	136000	305173.1
157	76	33337	M1	2.61	2.80	126400	329502.9
158	91	40297	M3	8.15	19.15	111200	906492.4
159	92	40571	M3	1.01	1.65	39600	40177.3
160	94	42170	M3	1.96	2.57	183200	359099.4
161	86	38623	M2	2.96	5.47	15250	45195.1
162	96	33627	M4	0.98	1.10	15800	15440.0
163	100	34622	M4	0.96	1.30	34700	33158.3
164	101	34780	M4	3.15	5.67	148400	467774.2
165	44	34854	G1	2.70	8.45	78375	211621.8
166	45	34895	G1	8.18	19.72	87104	712106.7
167	46	34928	G1	2.76	8.96	46896	129606.4
168	48	35180	G1	5.26	14.47	120975	636721.4
169	51	36159	G1	0.82	1.47	26100	21441.5
170	53	36267	G1	19.70	48.93	136928	2697263.4
171	54	38163	G1	2.52	6.64	29264	73803.4
172	56	38282	G1	3.35	9.98	56800	190106.7
173	57	38525	G1	2.34	11.60	242000	567198.4
174	59	33374	G2	2.45	10.74	55225	135540.2
175	105	39154	P1	1.69	2.16	27150	45889.4

Reference Codes

M1 Allott, T.E.H., Monteith D.T., Patrick, S.T., Duigan, C.A., Lancaster, J., Seda, M., Kirika, A., Bennion, H. & Harriman, R. (1994). *Integrated Classification and Assessment of Lakes in Wales: Phase I.* CCW Science Report No. 85. Countryside Council for Wales. Contract No. FC 73-01-71

M2 Monteith D.T. (ed) (1995). *Integrated Classification and Assessment of Lakes in Wales: Phase II.* CCW Science Report No. 128. Bangor, Countryside Council for Wales. Contract No. FC 73-01-71

M3 Monteith, (1996) Monteith, D.T. (ed) (1996). *Integrated Classification and Assessment of Welsh Lakes: Phase III.* CCW Science Report No. 167. Bangor, Countryside Council for Wales. Contract No. FC 73-01-71

M4 Monteith, 1997 Monteith D.T. (ed) (1997). *Integrated Classification and Assessment of Lakes in Wales: Phase IV.* CCW Science Report No. 214. Bangor, Countryside Council for Wales. Contract No. FC 73-01-71

H1 Holman IP, Gill A.B, Seymour I, Vale M. (2007). *Investigative Survey of Sediment Depth and Bathymetry of Bosherston Lakes, Pembrokeshire.* CCW Regional Report WW/07/6. Aberystwyth, Countryside Council for Wales.

W1 Wade et al. in prep, RPS.

P1 Perrow MR, Sayer CD, Skeate ER, Shilland EM, Goldsmith BJ, Hughes MJ. (2004). *The future management of Falcondale Lake, Site of Special Scientific Interest, Ceredigion.* CCW Contract Science Report 620. Bangor, Countryside Council for Wales.

B1 Burgess A, Goldsmith B, Hatton-Ellis T, Hughes M, Shilland E. (2009). *CCW Standing Waters SSSI Monitoring 2007-08.* CCW Contract Science Report 855. Bangor, Countryside Council for Wales.

G1 Goldsmith B, Bennion H, Hughes M, Jones V, Rose C, Simpson G. (2005). *Integrating Habitats Directive and Water Framework Directive Monitoring: Baseline Survey of Natura 2000 Standing Water Habitats in Wales.* CCW Contract Science Report 704. Bangor, Countryside Council for Wales.

G2 Goldsmith, B., Hughes, M. & Shilland, E. (2009) *Habitats Directive assessment of Llyn Anafon with respect to proposed water level changes*. Final Report to Mott MacDonald. ECRC Research Report 138.

G3 Goldsmith, B., Burgess, A., Bennion, H., Turner, S. D., Appleby, P. G. & Piliposian, G. T. (2010) *Palaeoecological and surface sediment analysis of Welsh SSSI / SAC lakes incorporating chemical and bathymetric surveys.* Report to CCW as part of Lake Macrophyte & Habitat Surveys for the Water Framework Directive, 2007-10. The Environment Agency. Contract No: 20457

ECRC	ECRC	Assorted.
EAW	EAW	Environment Agency Wales. Contact: Peter Clabburn
CEH	CEH	Centre for Ecology and Hydrology, Lancaster Environment Centre. Contact: IanWinfield

APPENDIX 8: Morphometric statistics from UK Lakes database of sites with bathymetric raster grids generated.

Table A8.1 Morphometric statistics from UK Lakes database of sites with bathymetric raster grids generated.

ID			From UKLakes dataset				
Bathy_ID	Dataset_ID	WBID	Area (ha)	Perimeter (m)	Altitude (m)	SDI	Max Fetch (m)
100	3	32746	39.1	3365	36	1.52	1235.64
101	4	33160	23.8	2222	5	1.28	817.94
102	5	33631	1.6	524	275	1.16	192.43
103	6	33864	1.3	523	262	1.29	226.99
104	7	34813	1.1	457	89	1.23	195.02
105	8	37168	8.3	1385	389	1.36	562.27
106	9	37617	12.3	1529	177	1.23	648.51
107	10	38321	3.4	777	228	1.18	308.76
108	11	38544	5.3	1147	309	1.41	471.26
109	12	39267	9.7	1353	298	1.22	563.39
110	13	39796	10.1	1241	109	1.1	492.87
111	14	39813	6.4	1129	109	1.26	464.94
112	15	40338	1.3	930	8	2.31	278.29
113	16	41973	7.8	3259	4	3.3	532.29
114	17	42721	6.2	1121	18	1.27	389.88
115	18	36535	1.1	460	75	1.26	176.1
116	20	33843	0.6	374	660	1.32	155.79
117	118	34987	415.2	15018	158	2.08	5661.44
118	119	34864	35.1	2300	405	1.075	785
119	22	34243	5.9	1204	548	1.4	410.39
120	120	34002	90.1	4454	142	1.32	1920.48
121	23	34319	5.1	840	375	1.05	289.1
122	21	33962	26.3	2062	384	1.13	805.13
123	19	33730	97.6	7680	105	2.19	3206.77
124	24	34633	13.5	1638	455	1.26	649.61
125	26	35650	9.4	1227	317	1.13	487.02
126	28	34044	0.5	0.3	528	1.073	92
127	29	37437	9.2	1638	458	1.53	726.42
128	30	37834	5.6	1185	529	1.41	528.41
129	31	38394	5.1	1478	439	1.84	678.77
130	32	38422	10.1	1540	304	1.37	591.67
131	25	35426	5.1	952	539	1.19	367.07
132	60	33862	4.2	1137	555	1.56	311.38
133	61	34153	8.8	1629	65	1.55	745.75
134	62	35439	2.3	615	445	1.15	238.76
135	38	33836	13.2	1990	370	1.55	750.14
136	27	37080	3	781	194	1.27	317.71
137	63	41602	33.7	8902	2	4.32	1329.25
138	106	32640	0.8	359	138	1.13	141.85
139	110	34821	0.8	428	84	1.35	194.87
140	111	34916	2.2	718	9	1.37	315.06
141	113	35834	0.7	513	76	1.73	204.44
142	116	38856	3.4	731	366	1.12	277.65
143	117	39890	2.1	612	58	1.21	197.89
144	36	33374	4.3	886	502	1.2	341.48
145	35	32792	1.2	422	77	1.1	159.76
146	40	34051	1	432	528	1.21	160.86
147	39	33974	10.7	1495	385	1.29	497.76
148	42	34632	2.8	700	503	1.17	251.03
149	43	34845	3.8	847	425	1.22	270.65
150	47	35056	9.9	1589	355	1.43	660.73
151	49	35233	3.5	1159	385	1.74	455.53

ID			From UKLakes dataset				
Bathy_ID	Dataset_ID	WBID	Area (ha)	Perimeter (m)	Altitude (m)	SDI	Max Fetch (m)
152	52	36177	0.7	314	488	1.06	115.03
153	55	38240	12	1616	519	1.32	677.23
154	50	35444	0.8	348	469	1.09	131.89
155	74	32948	9.7	1851	8	1.67	572
156	75	32968	22.3	2936	8	1.75	647.68
157	76	33337	28	2536	9	1.35	873.22
158	91	40297	15.5	1872	608	1.34	693.12
159	92	40571	5.3	963	238	1.19	354.42
160	94	42170	29.2	2450	15	1.28	896.68
161	86	38623	1.9	533	169	1.1	195.73
162	96	33627	2.4	805	8	1.46	361.58
163	100	34622	5.8	1091	129	1.27	379.74
164	101	34780	18.3	2178	79	1.44	910.87
165	44	34854	7.2	1202	388	1.26	520.15
166	45	34895	8.7	1806	448	1.73	604.43
167	46	34928	4.6	973	309	1.27	406.17
168	48	35180	13.6	1997	158	1.53	779.96
169	51	36159	2.7	682	416	1.18	285.95
170	53	36267	13.5	1562	478	1.2	598.33
171	54	38163	3.1	657	438	1.06	242.56
172	56	38282	6	1231	498	1.42	502.75
173	57	38525	23.3	2447	427	1.43	786.16
174	59	33374	4.3	886	502	1.2	341.48
175	105	39154	2.7	643	169	1.09	247.32

Appendix 9: Llyn Anafon (33374). R: output compilation pdf.

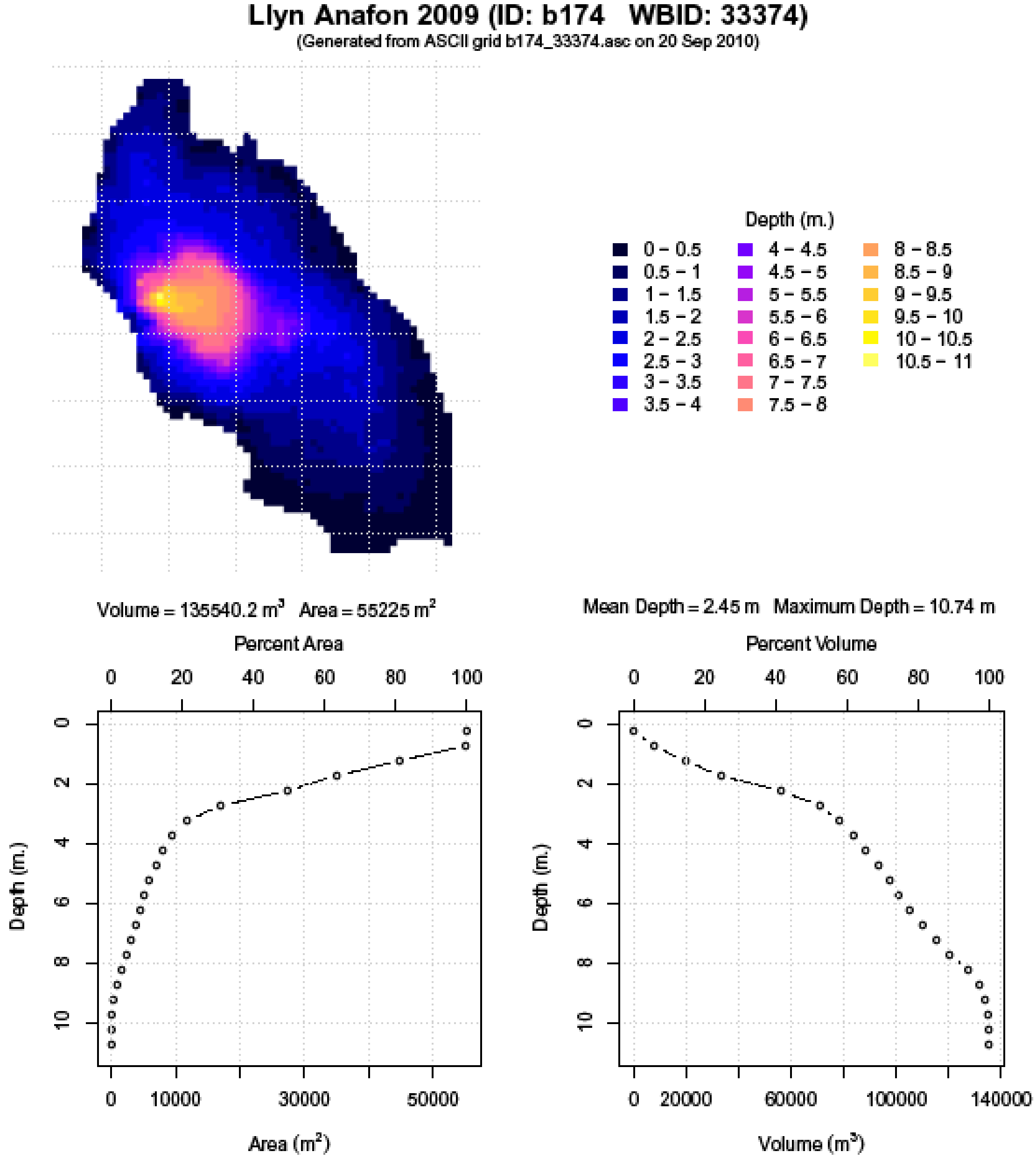


Figure A9.1 R: output compilation figure of Llyn Anafon

Appendix 10: Cosmeston Park (42721). R: output compilation pdf.

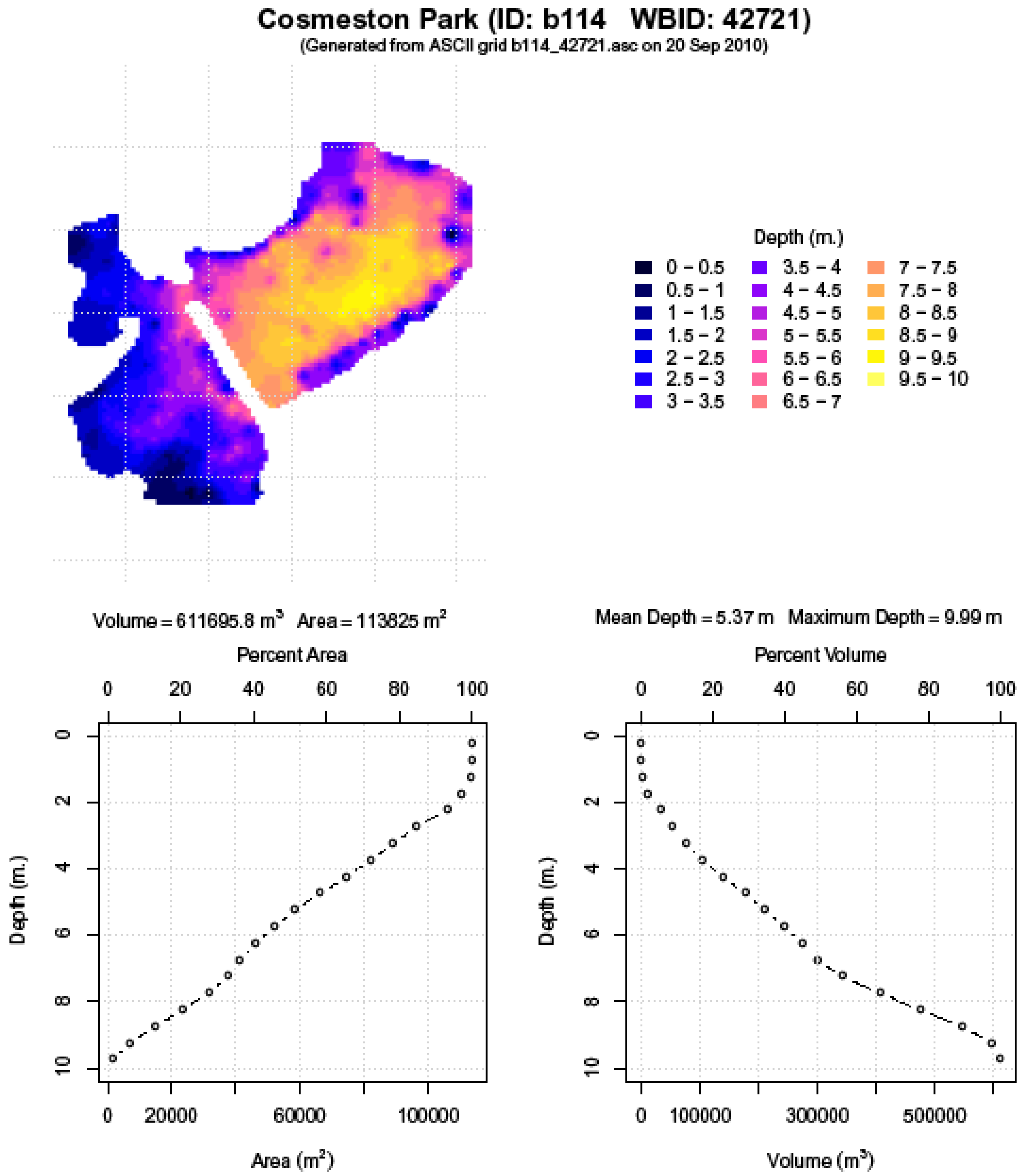


Figure A10.1 R: output compilation figure of Cosmeston Park

Appendix 11: R: output pdfs compilation. In order of WBID number.

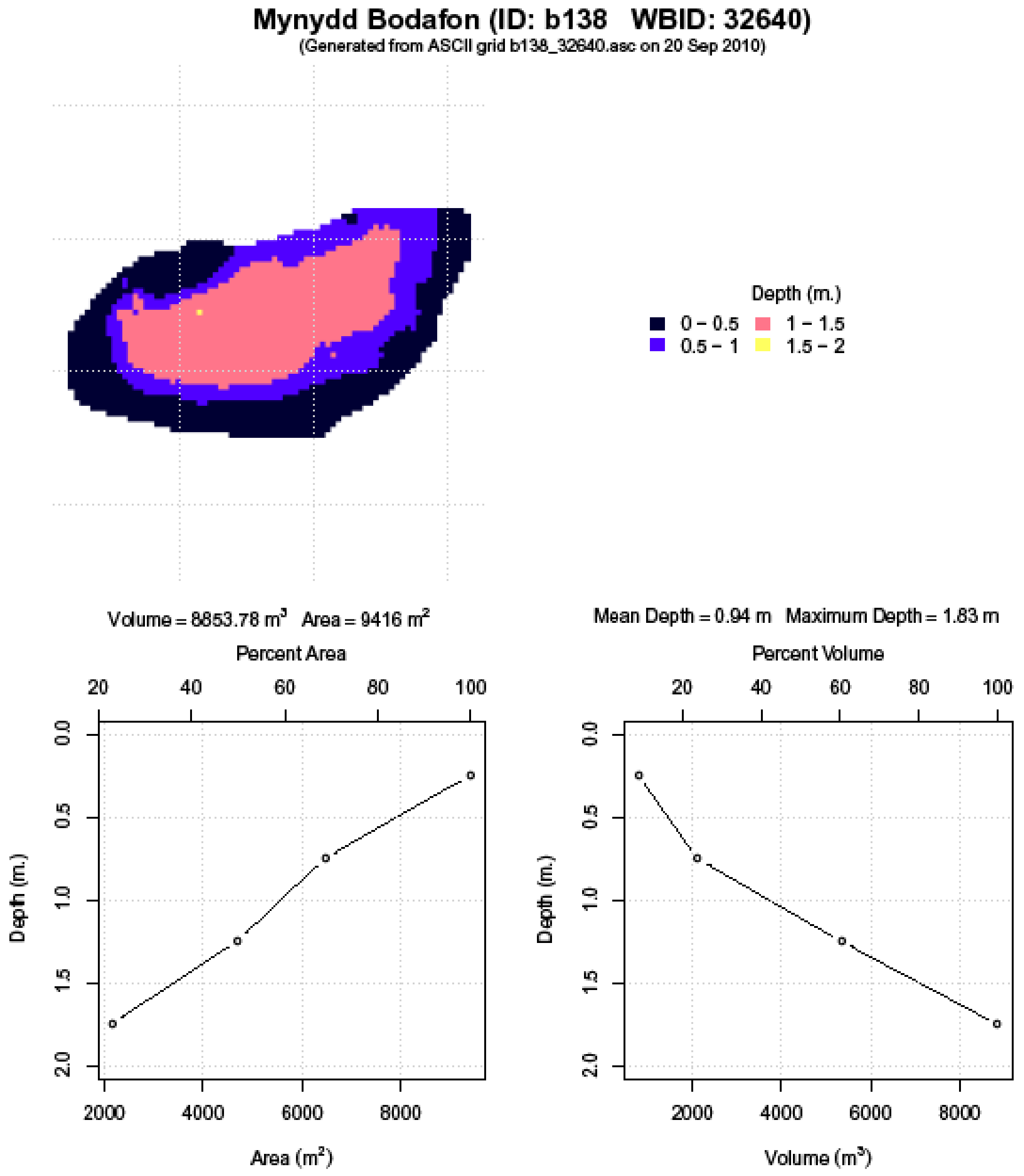


Figure A11.1 R: output compilation figure of Mynydd Bodafon

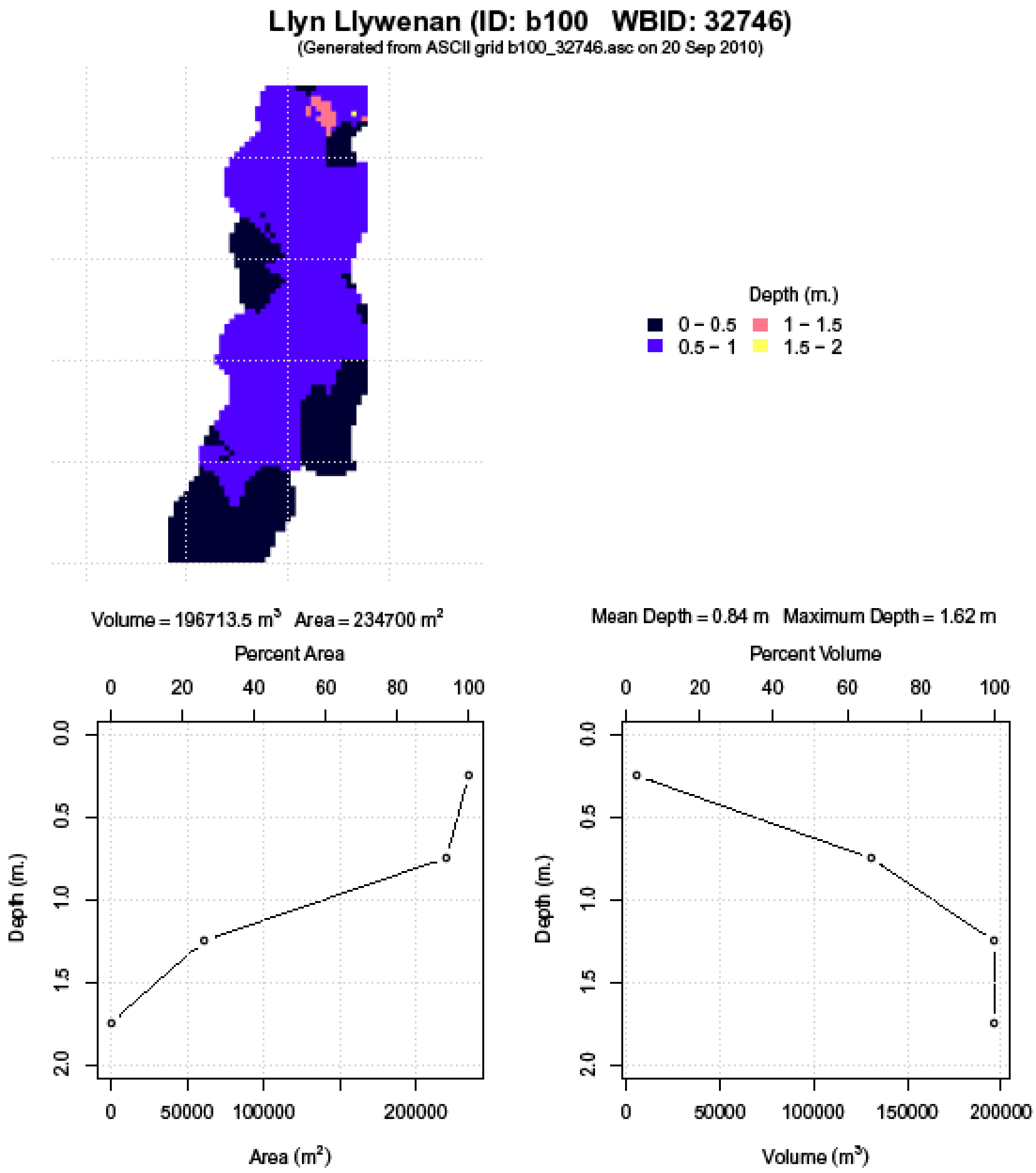


Figure A11.2 R: output compilation figure of Llyn Llywenan

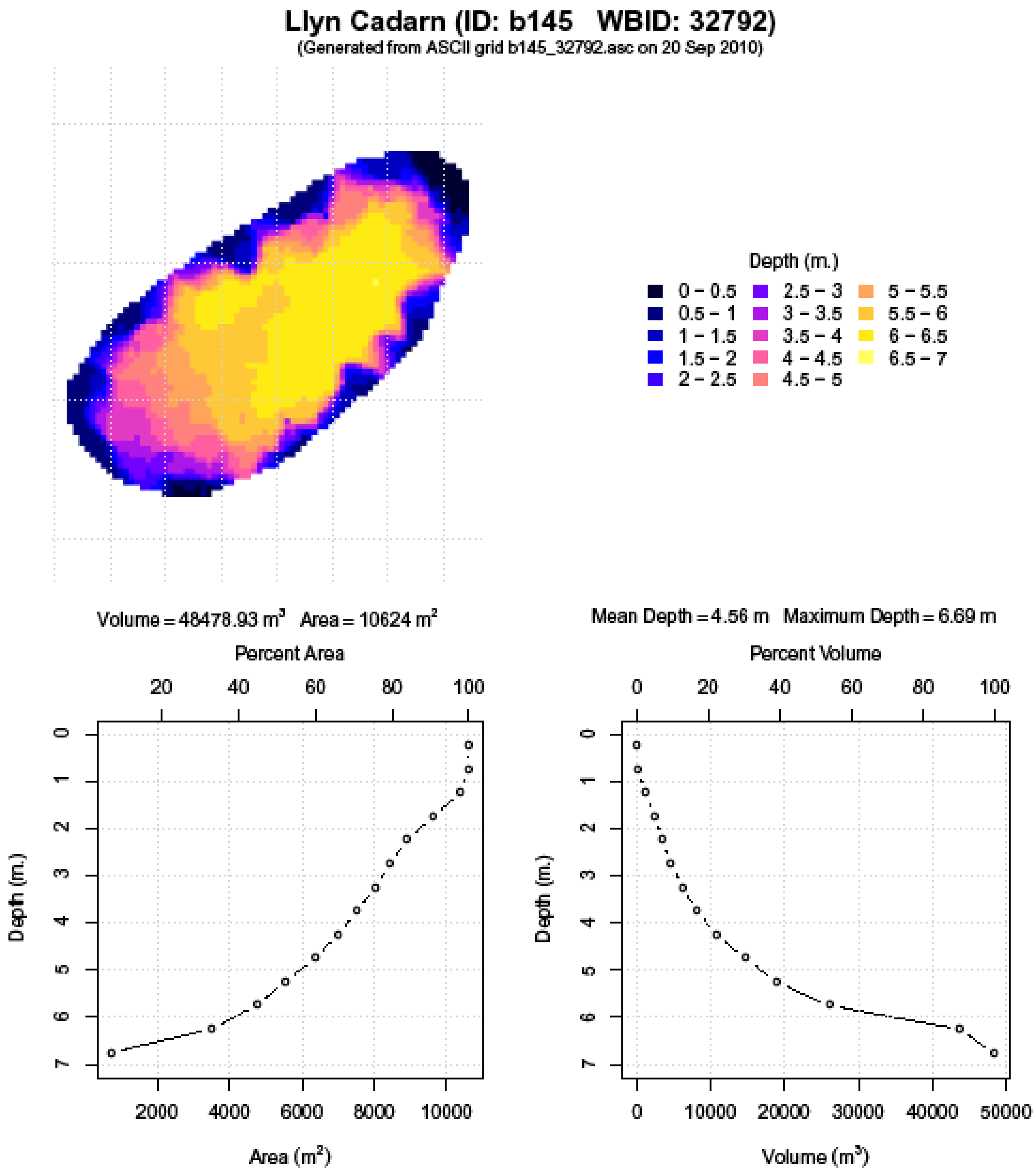


Figure A11.3 R: output compilation figure of Llyn Cadarn

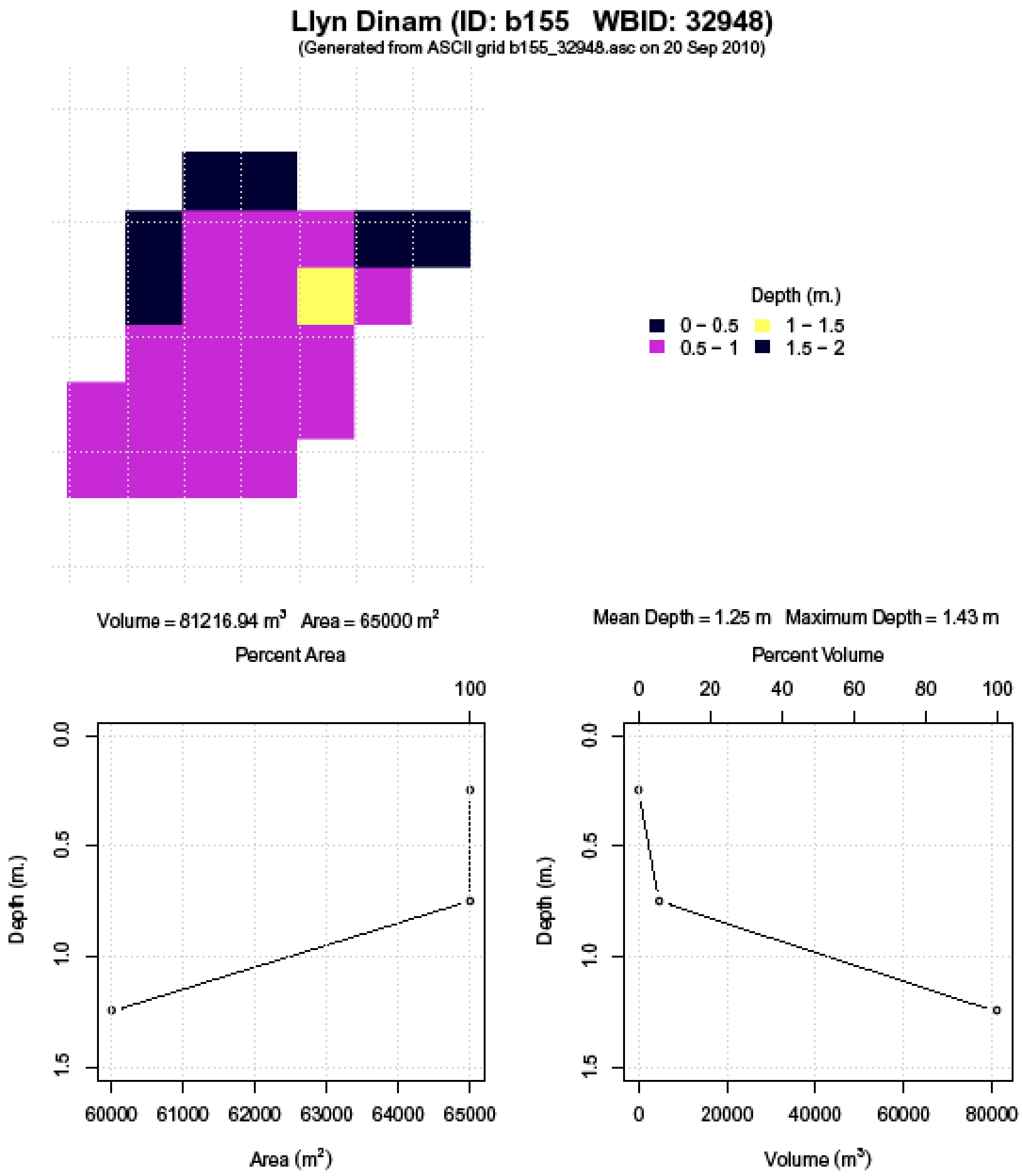


Figure A11.4 R: output compilation figure of Llyn Dinam

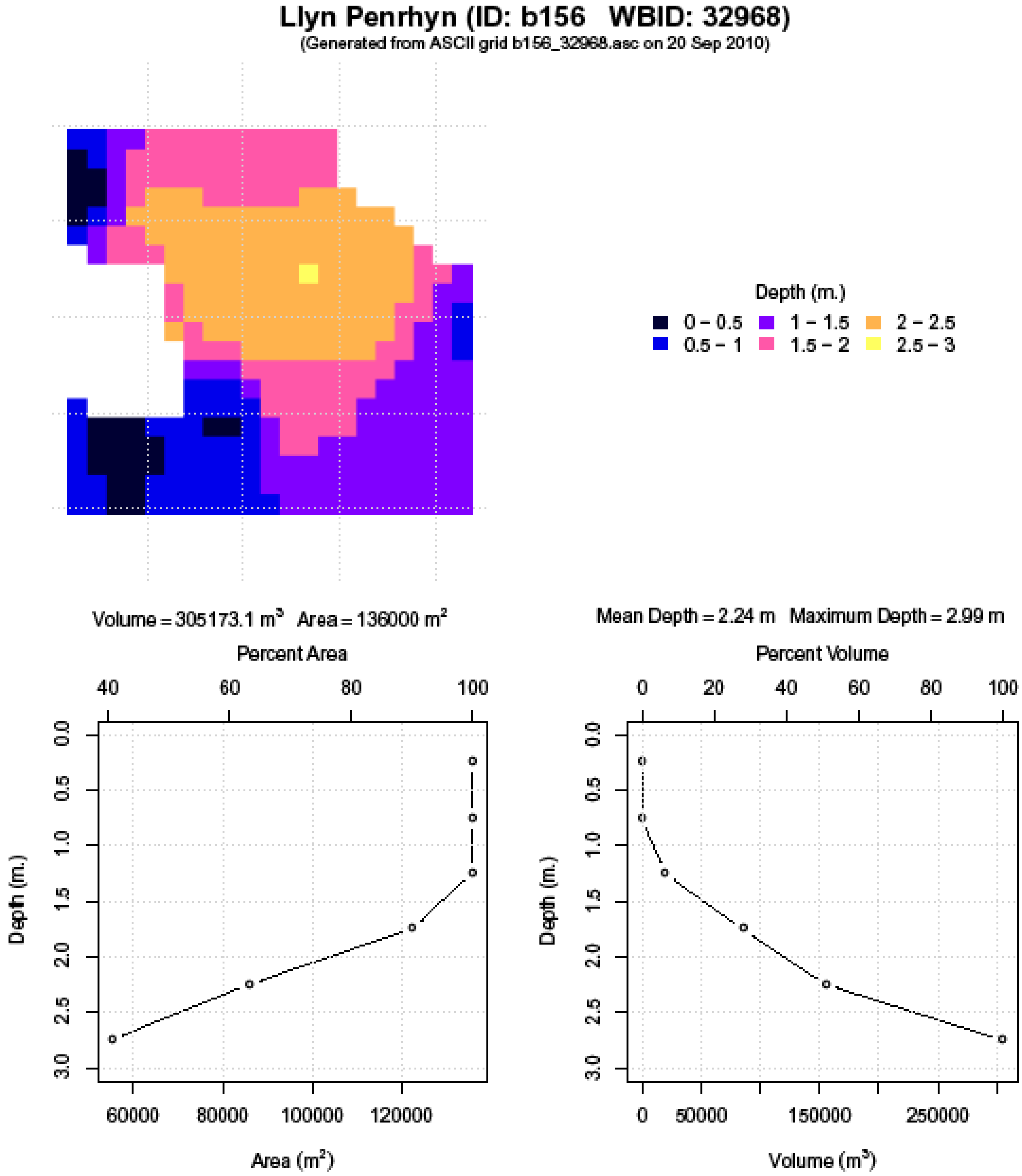


Figure A11.5 R: output compilation figure of Llyn Penrhyn

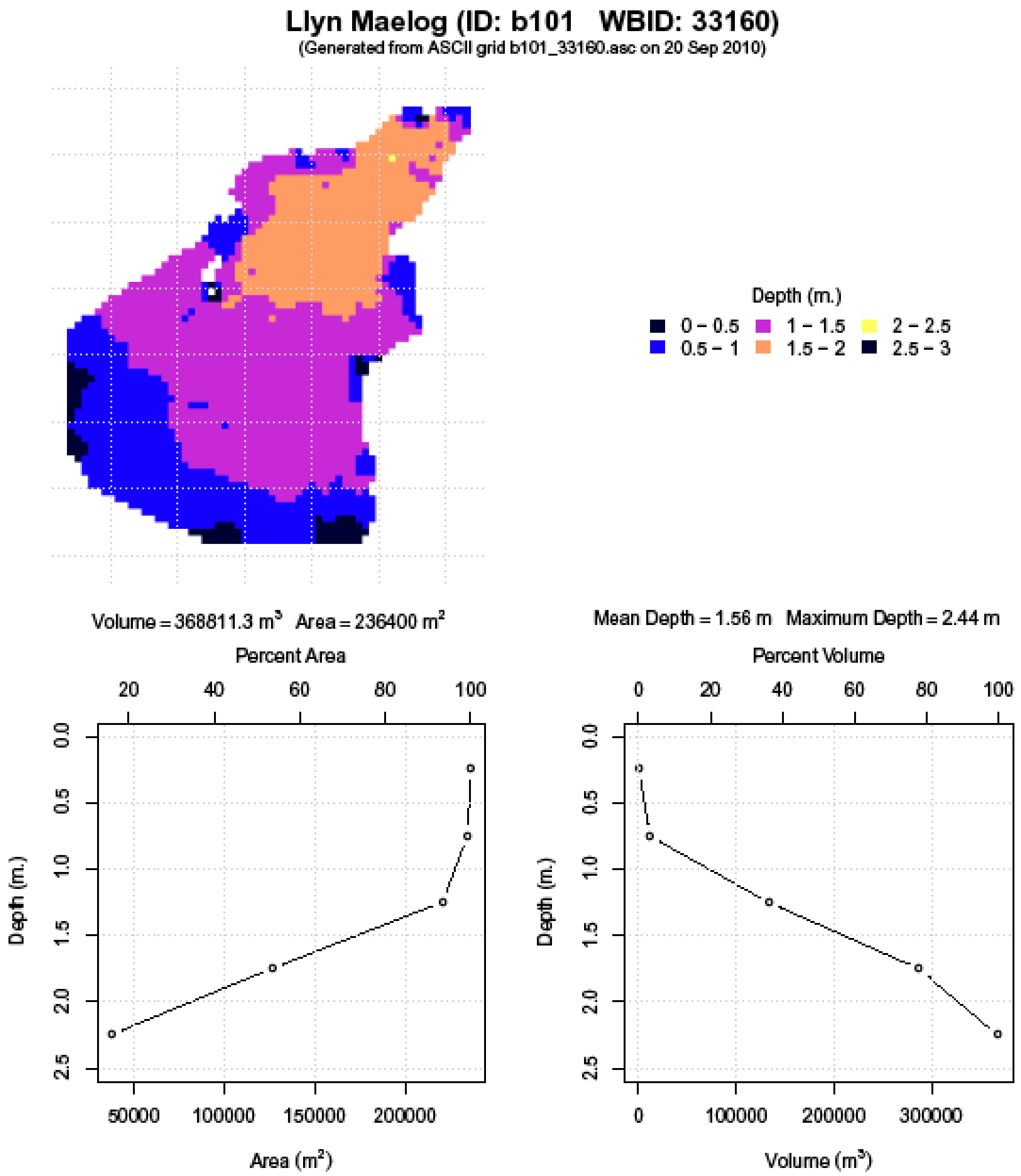


Figure A11.6 R: output compilation figure of Llyn Maelog

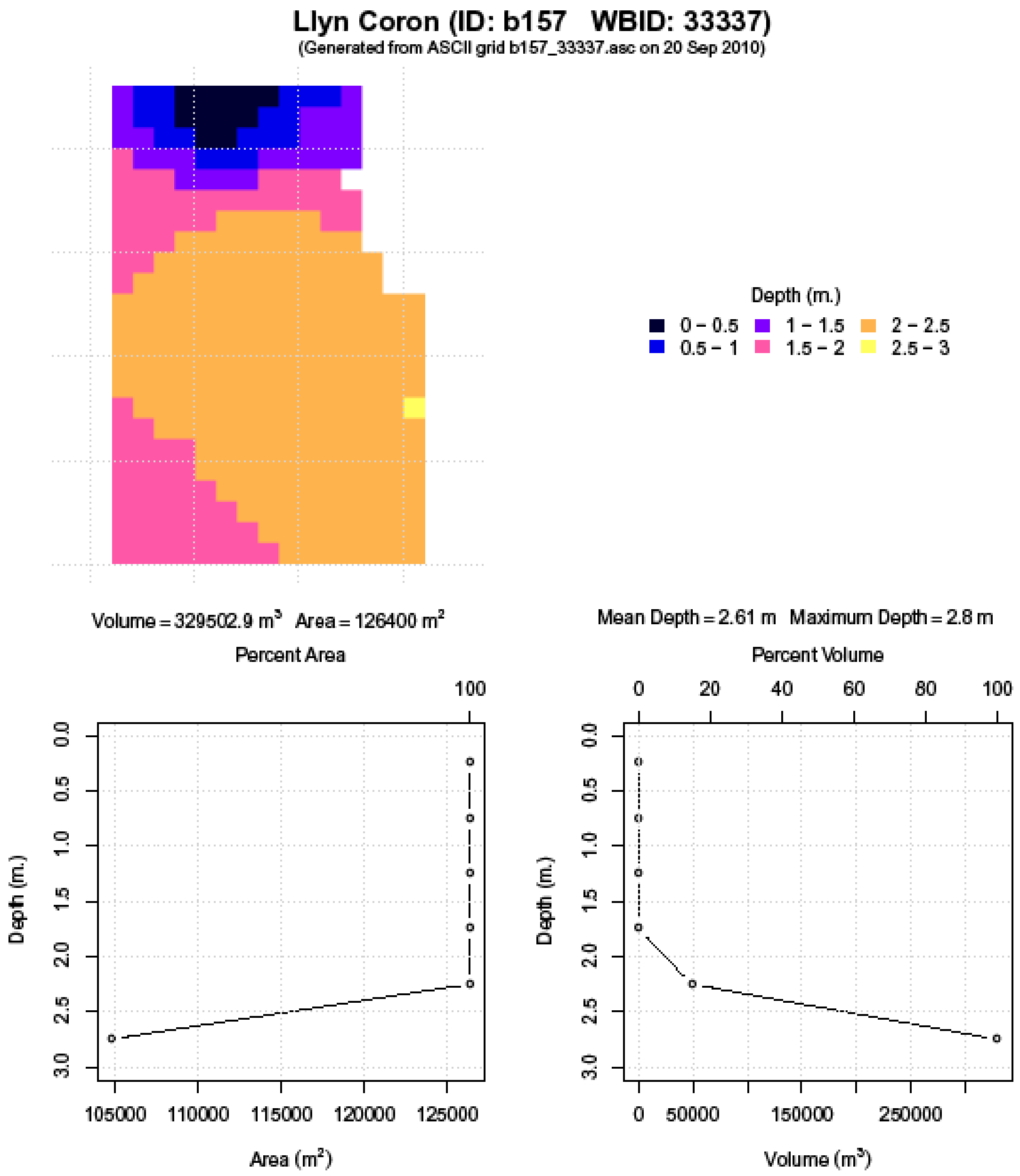


Figure A11.7 R: output compilation figure of Llyn Coron

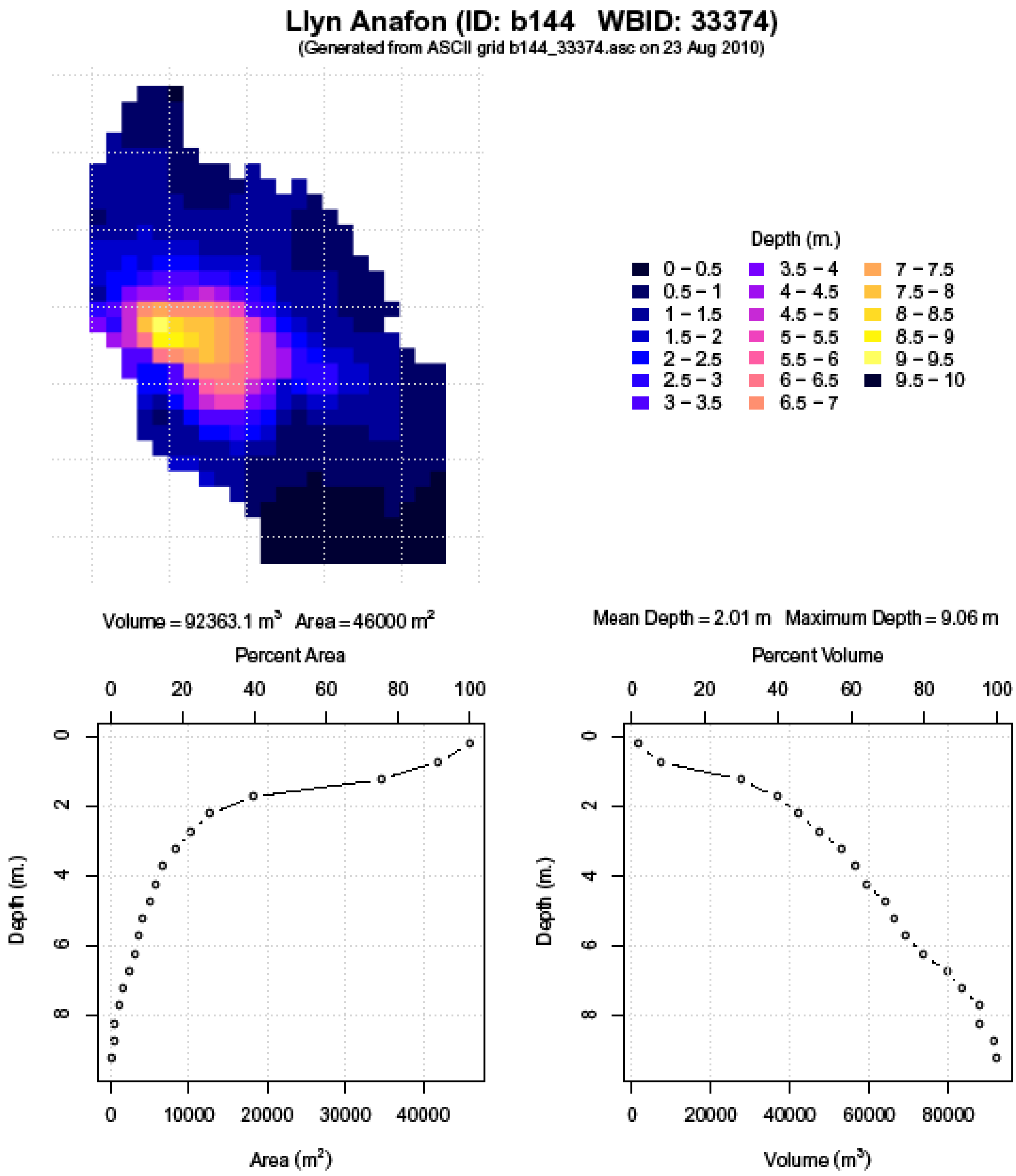


Figure A11.8 R: output compilation figure of Llyn Anafon

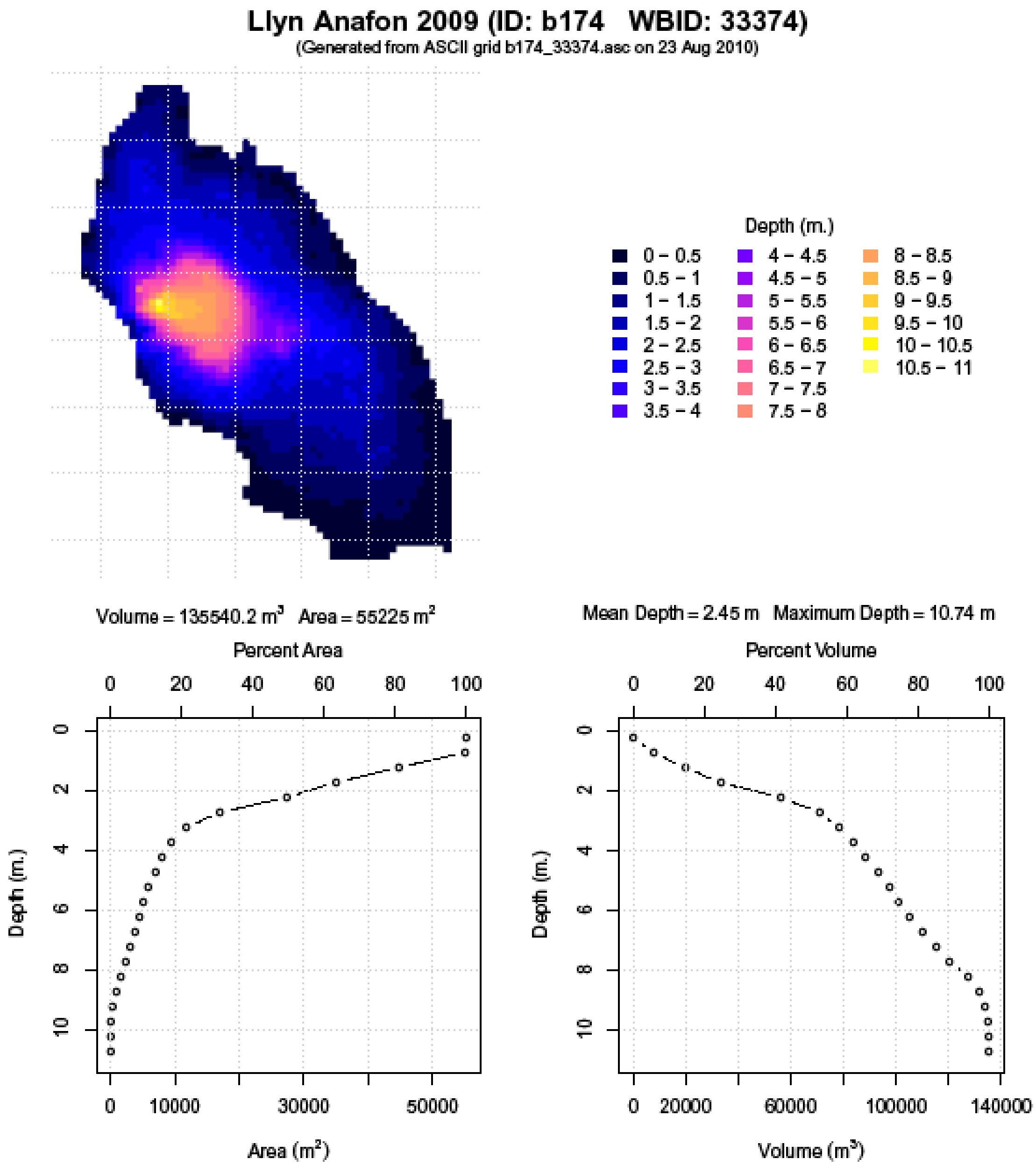


Figure A11.9 R: output compilation figure of Llyn Anafon 2009

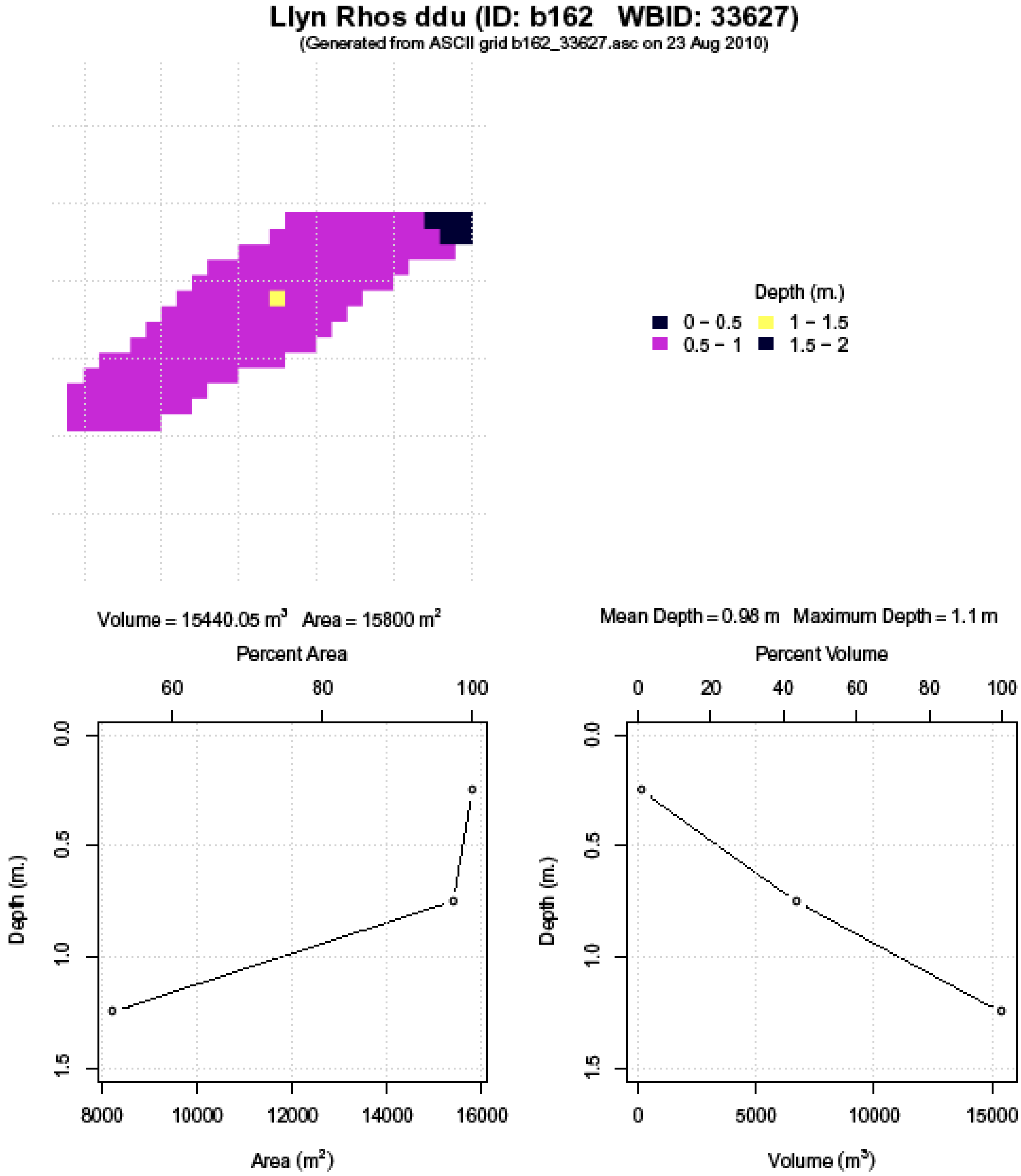


Figure A11.10 R: output compilation figure of Llyn Rhos ddu

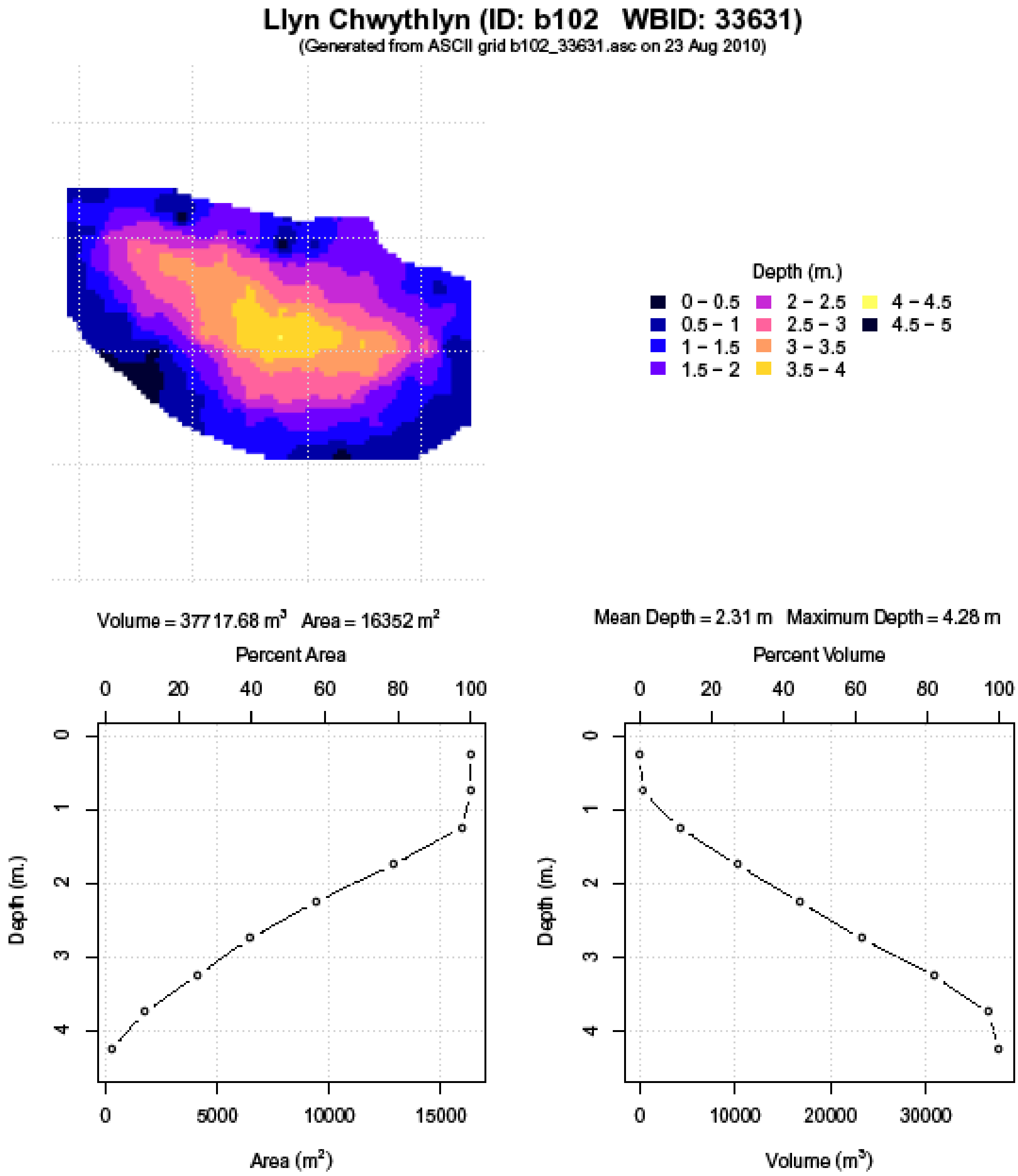


Figure A11.11 R: output compilation figure of Llyn Chwythlyn

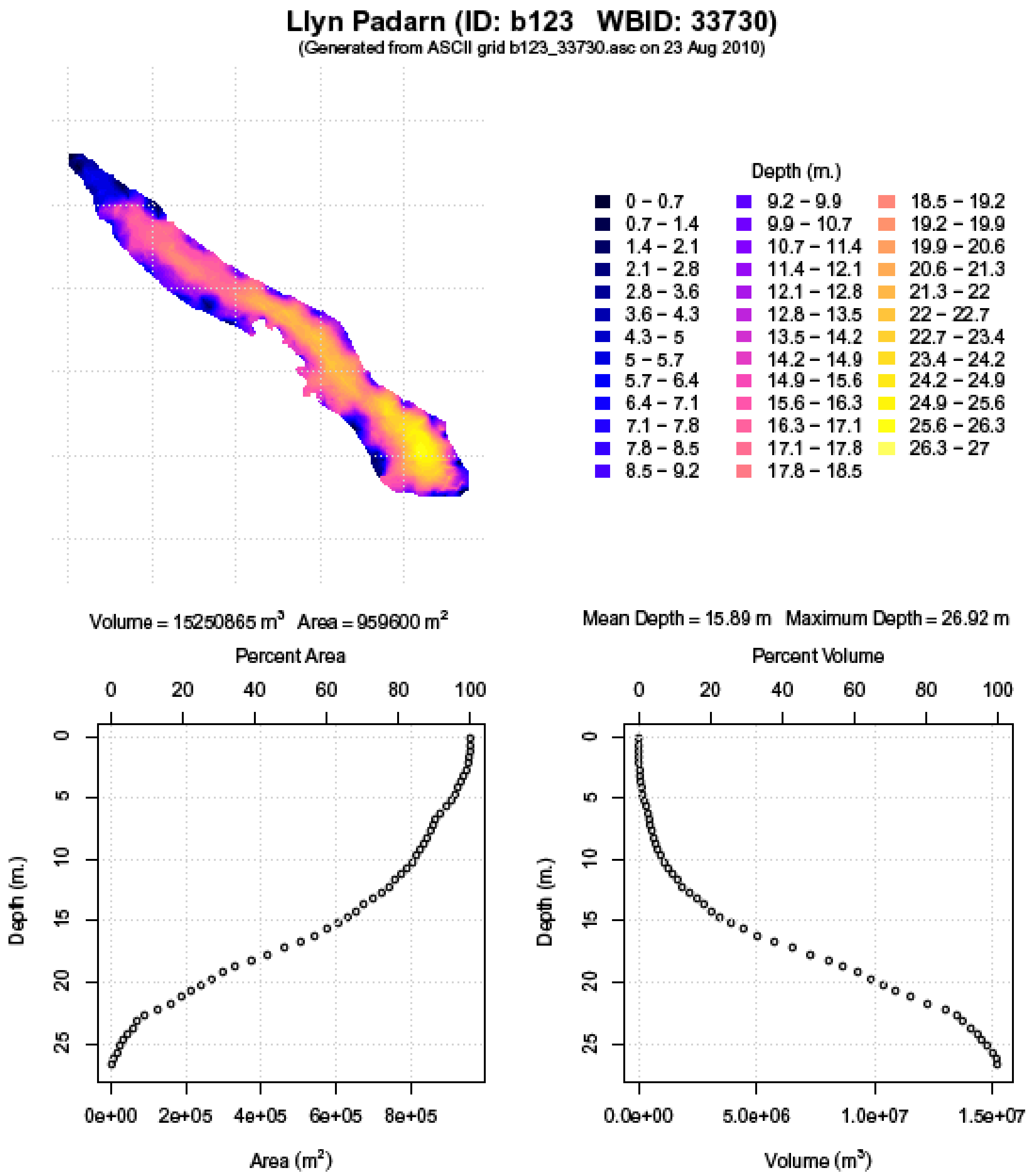


Figure A11.12 R: output compilation figure of Llyn Padarn

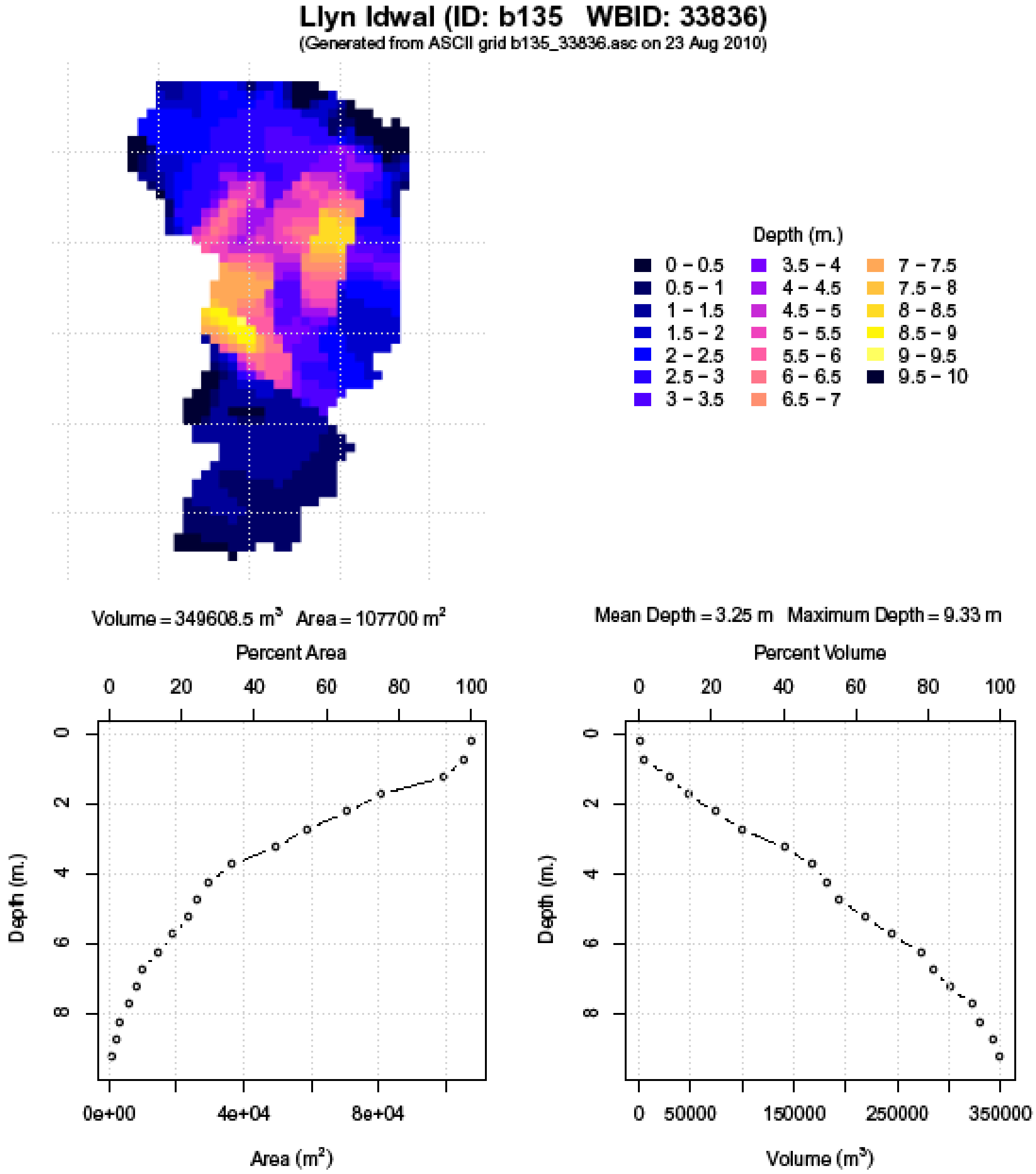


Figure A11.13 R: output compilation figure of Llyn Idwal

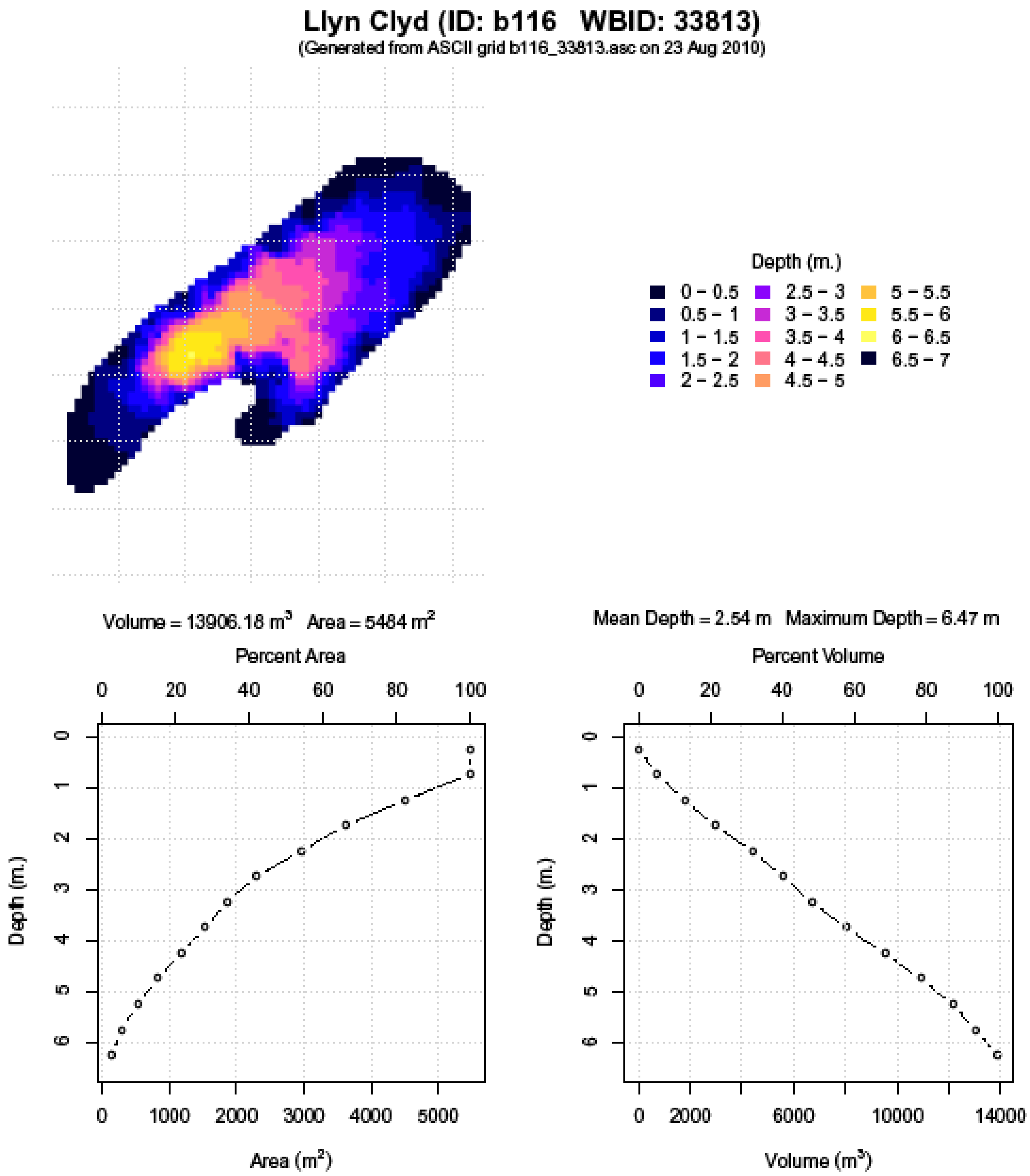


Figure A11.14 R: output compilation figure of Llyn Clyd

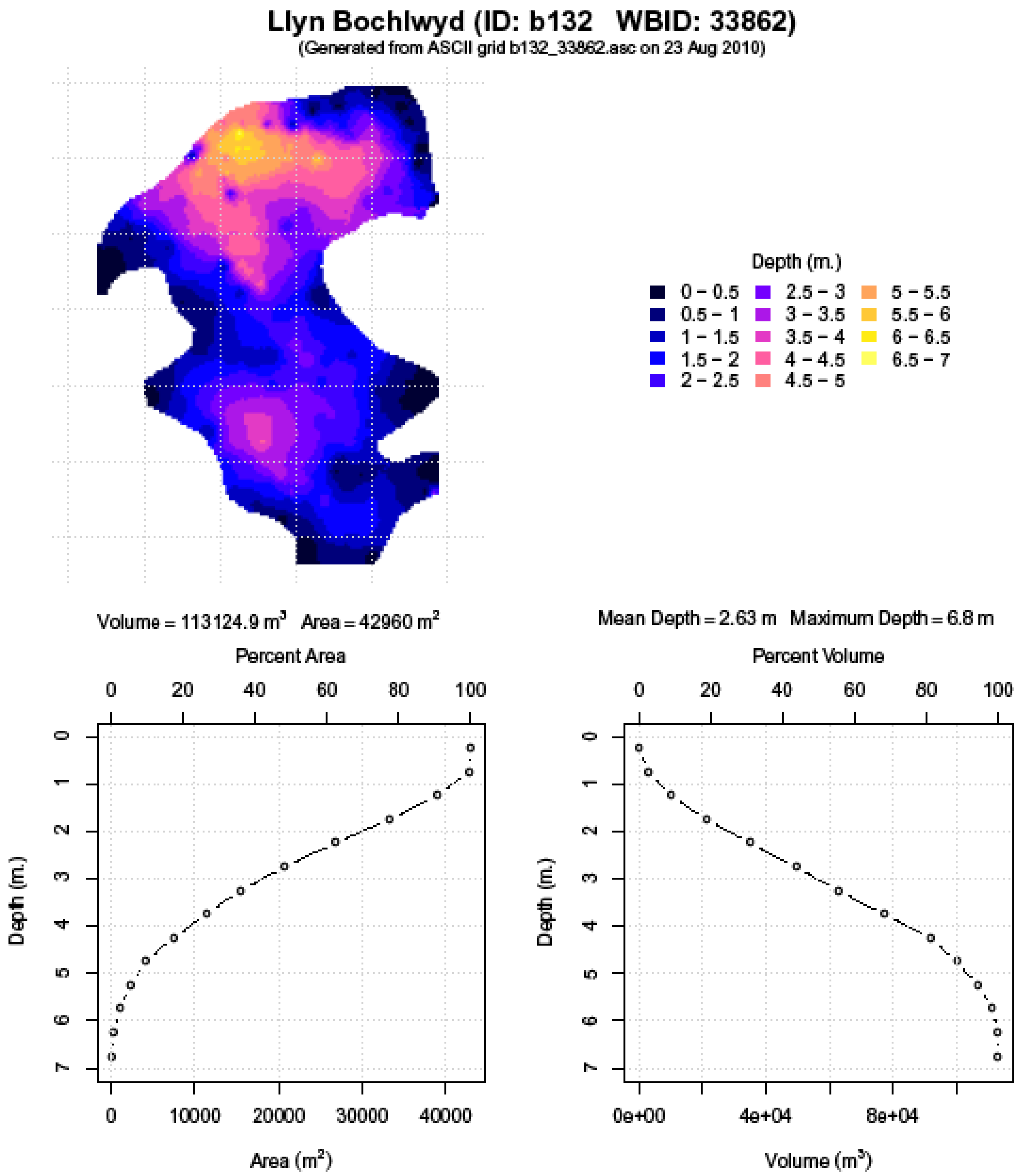


Figure A11.15 R: output compilation figure of Llyn Bochlwyd

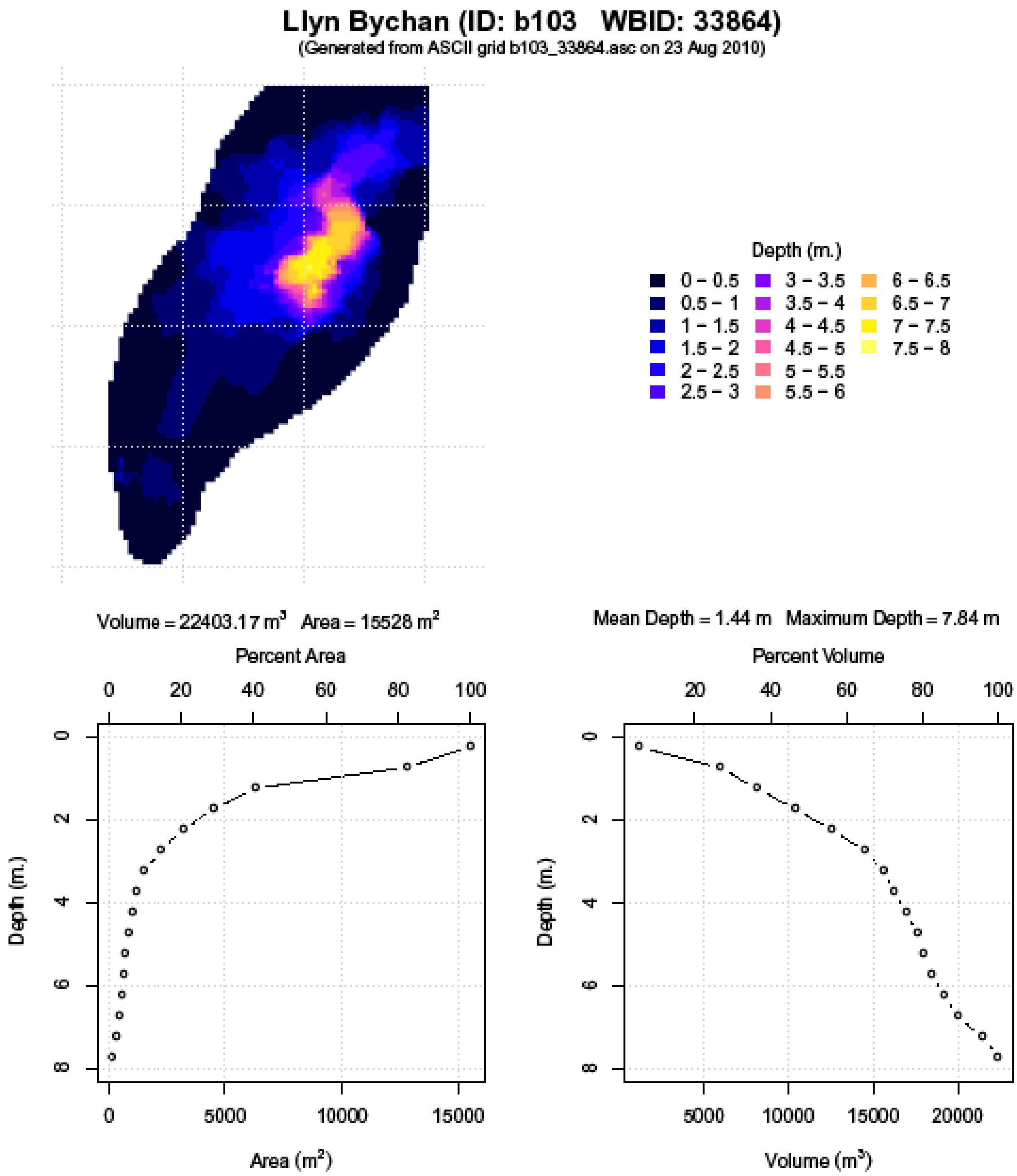


Figure A11.16 R: output compilation figure of Llyn Bychan

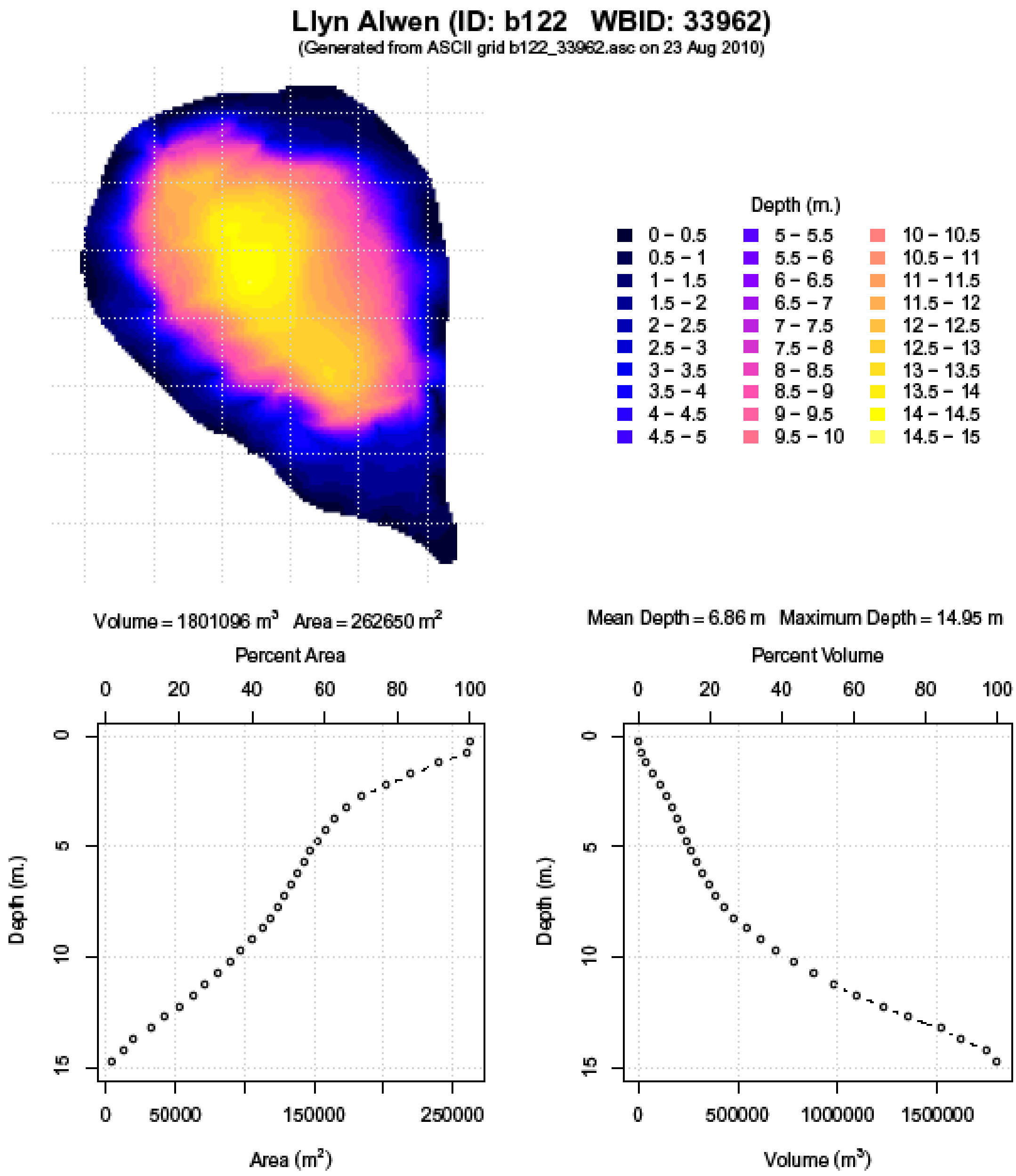


Figure A11.17 R: output compilation figure of Llyn Alwen

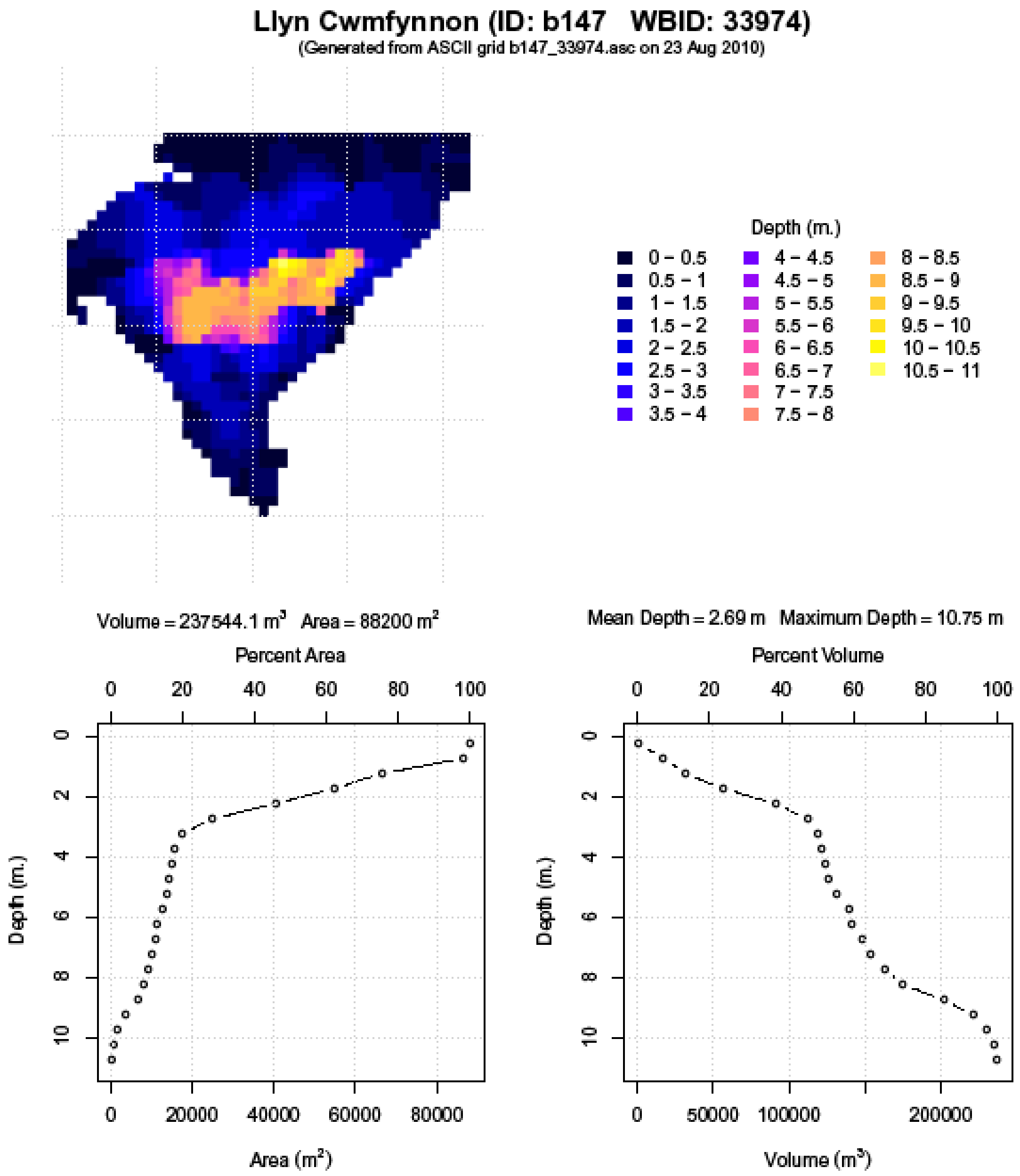


Figure A11.18 R: output compilation figure of Llyn Cwmfynnon

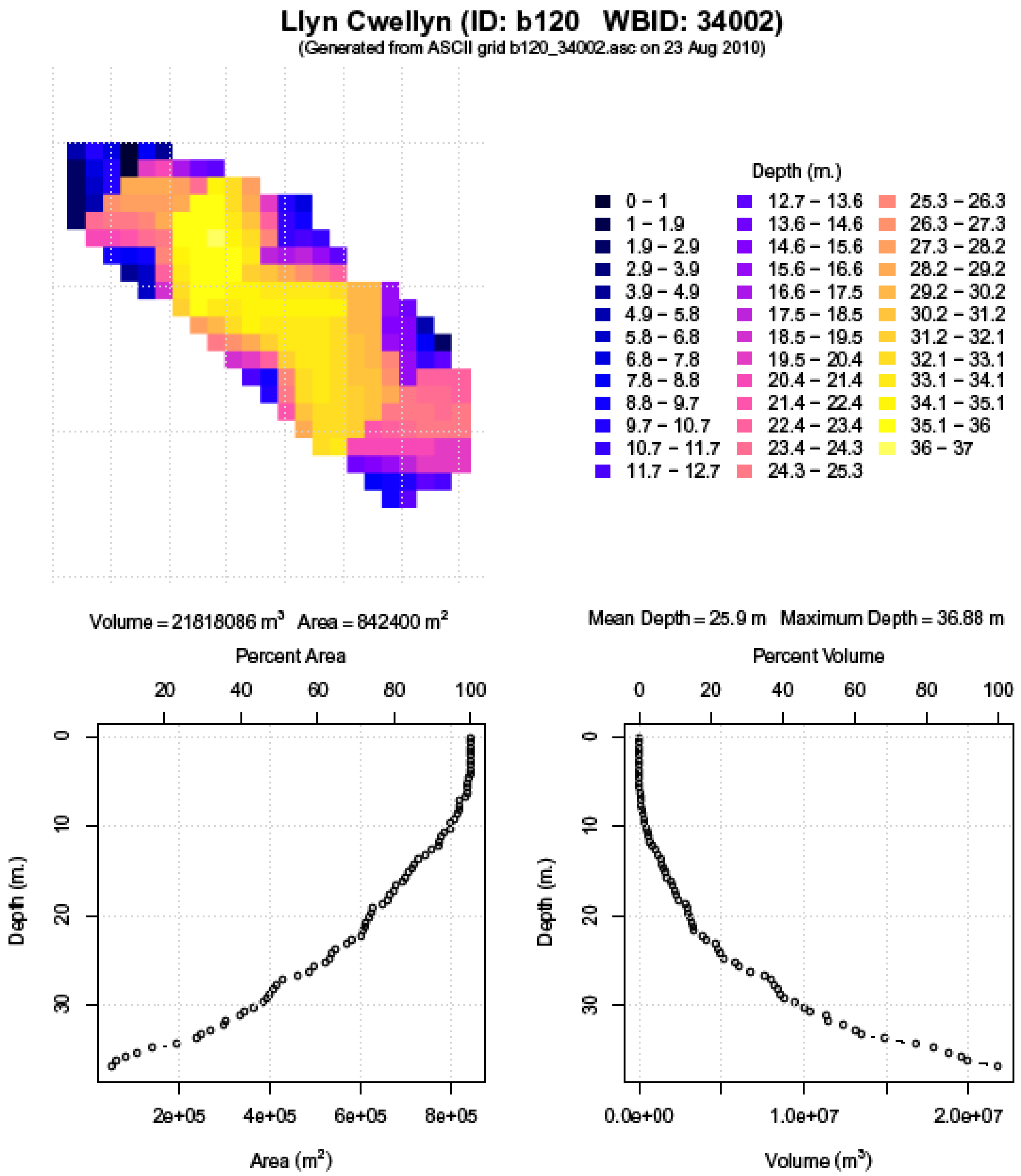


Figure A11.19 R: output compilation figure of Llyn Cwellyn

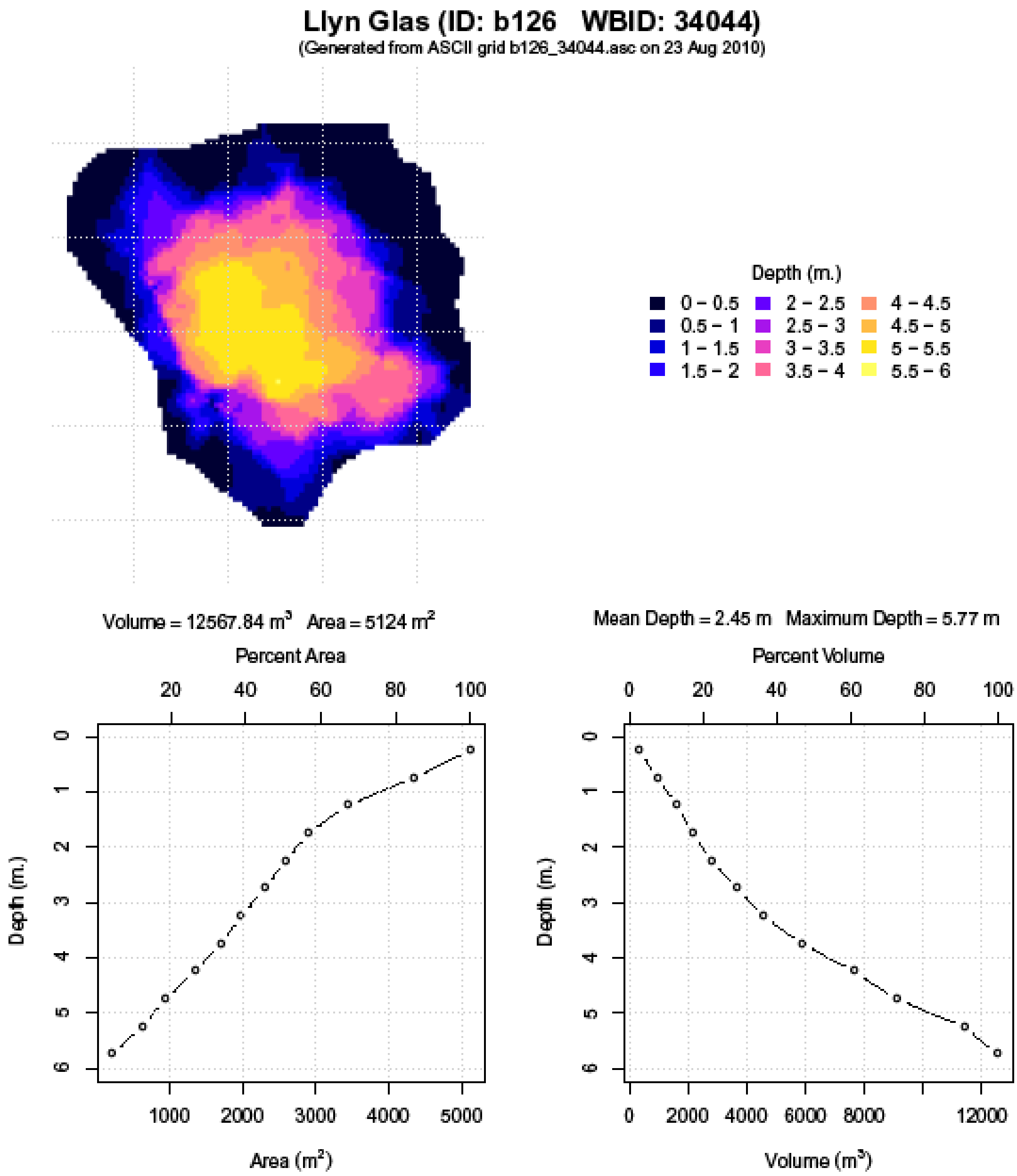


Figure A11.20 R: output compilation figure of Llyn Glas

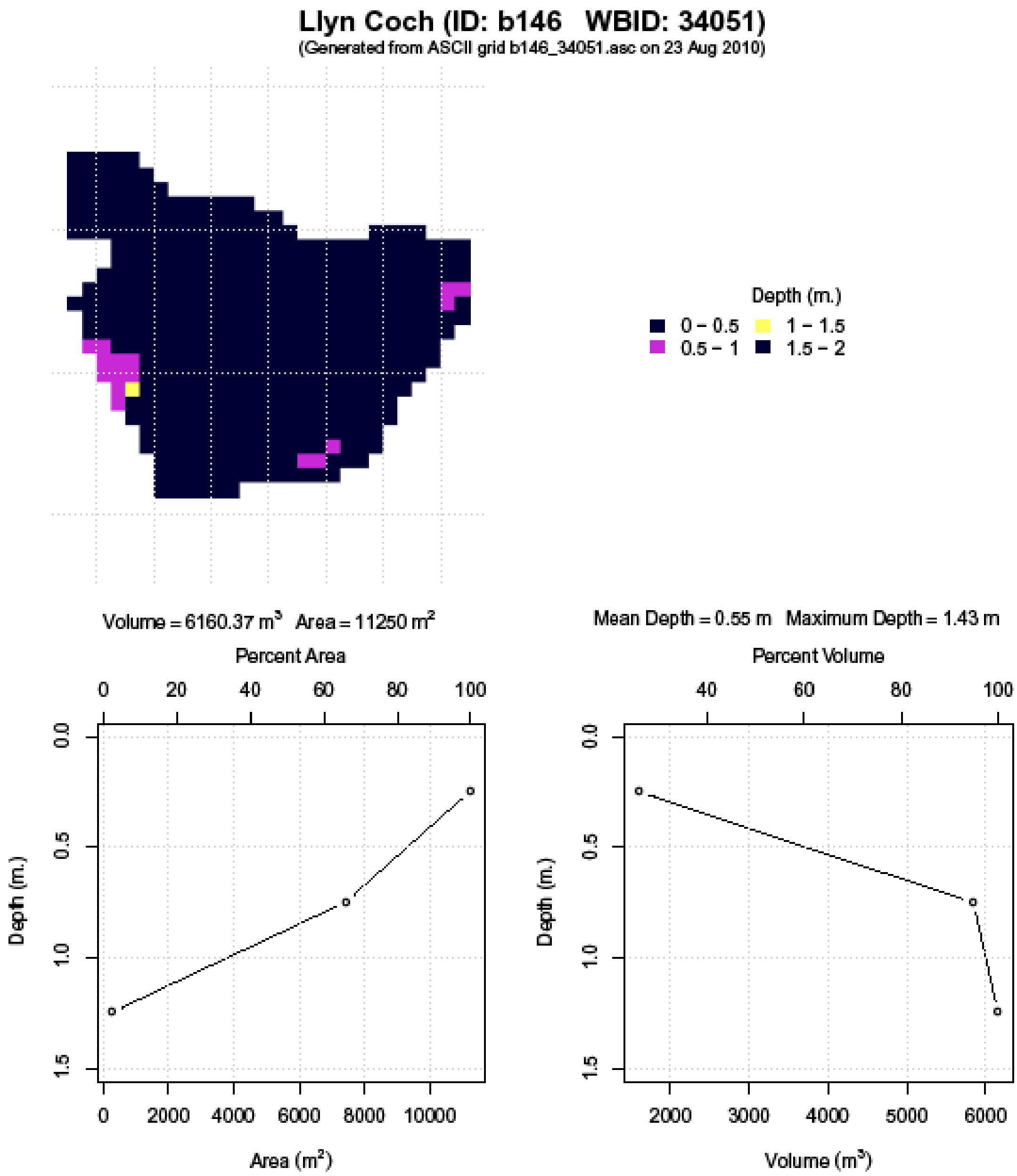


Figure A11.21 R: output compilation figure of Llyn Coch

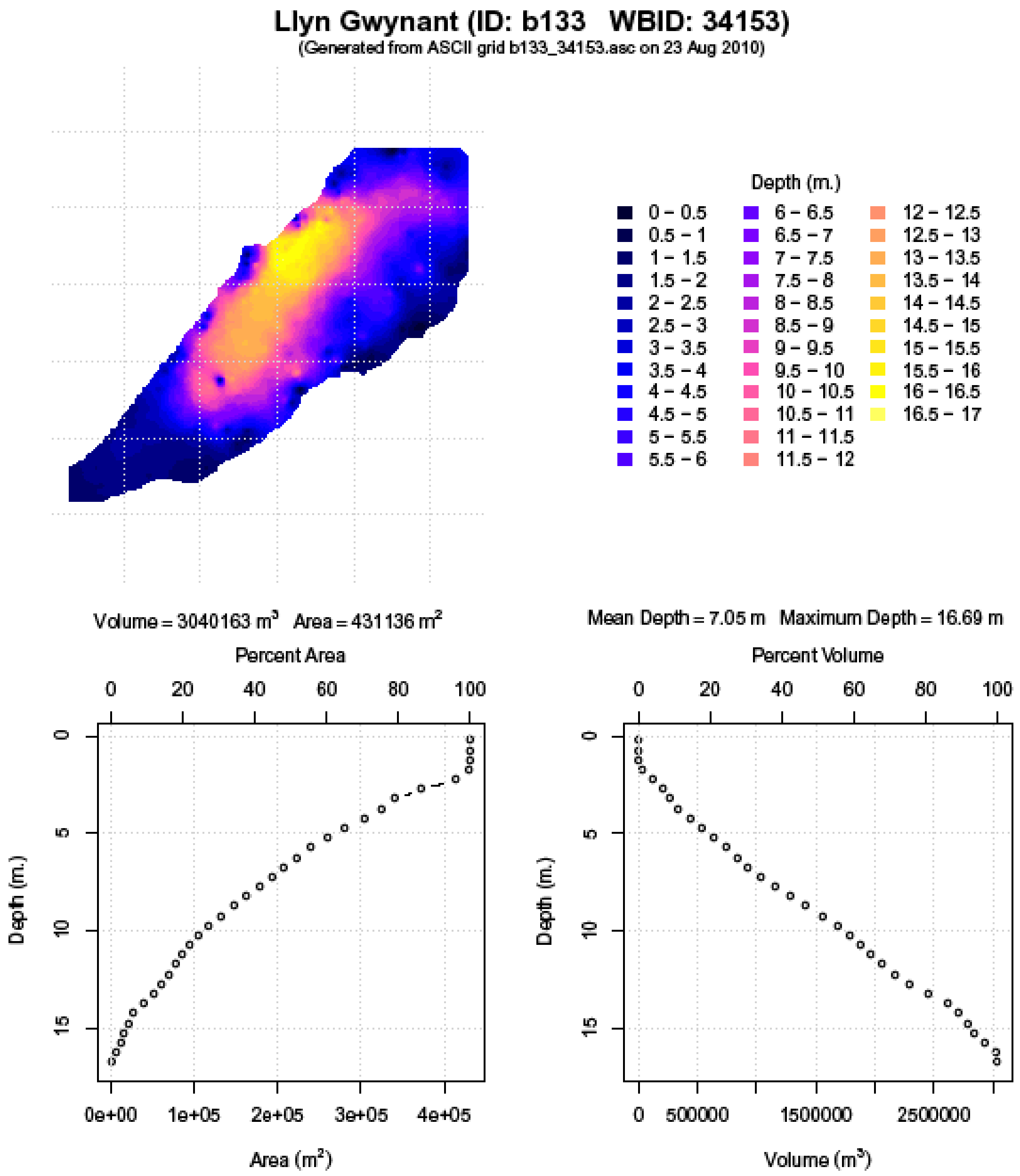


Figure A11.22 R: output compilation figure of Llyn Gwynant

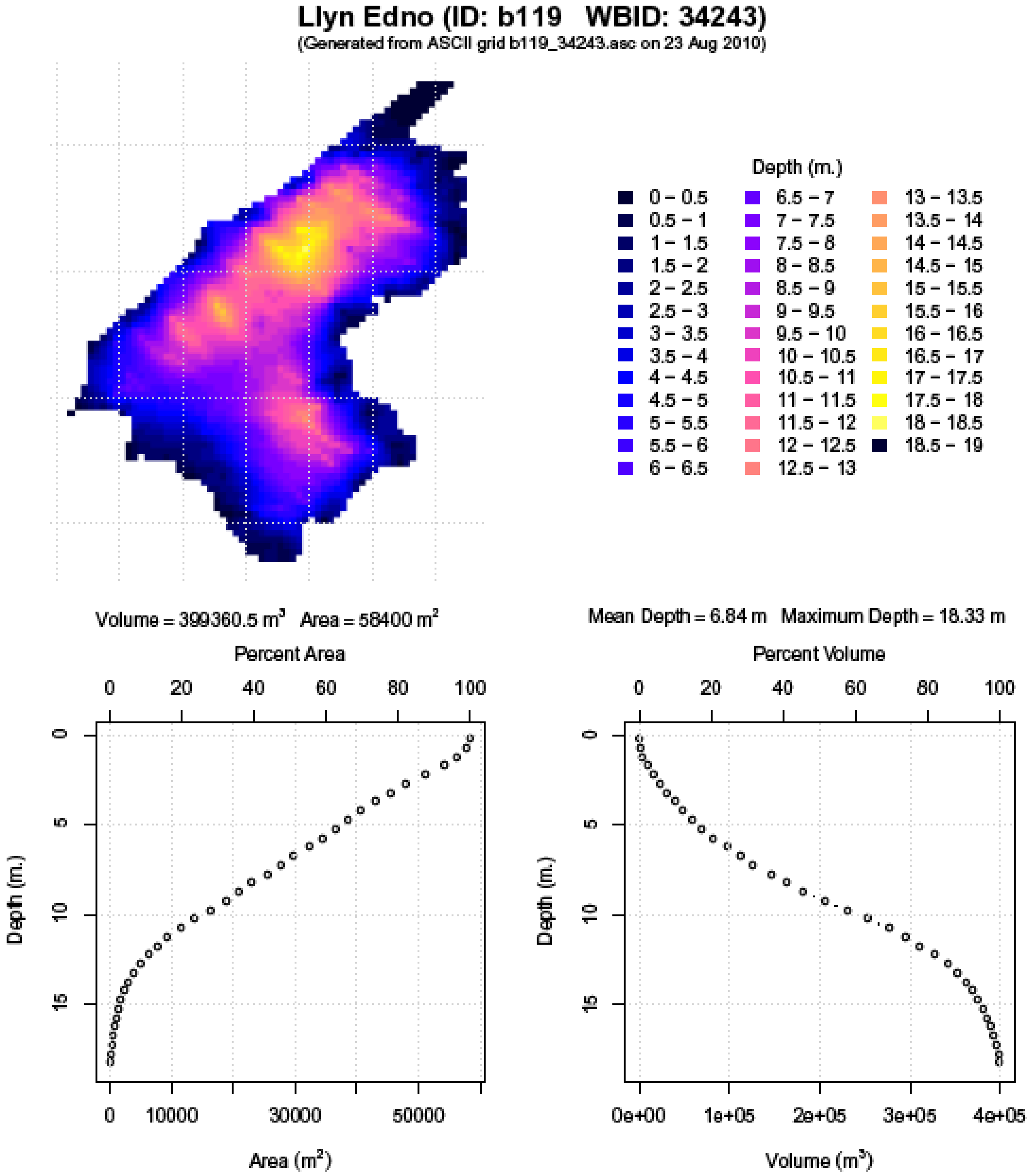


Figure A11.23 R: output compilation figure of Llyn Edno

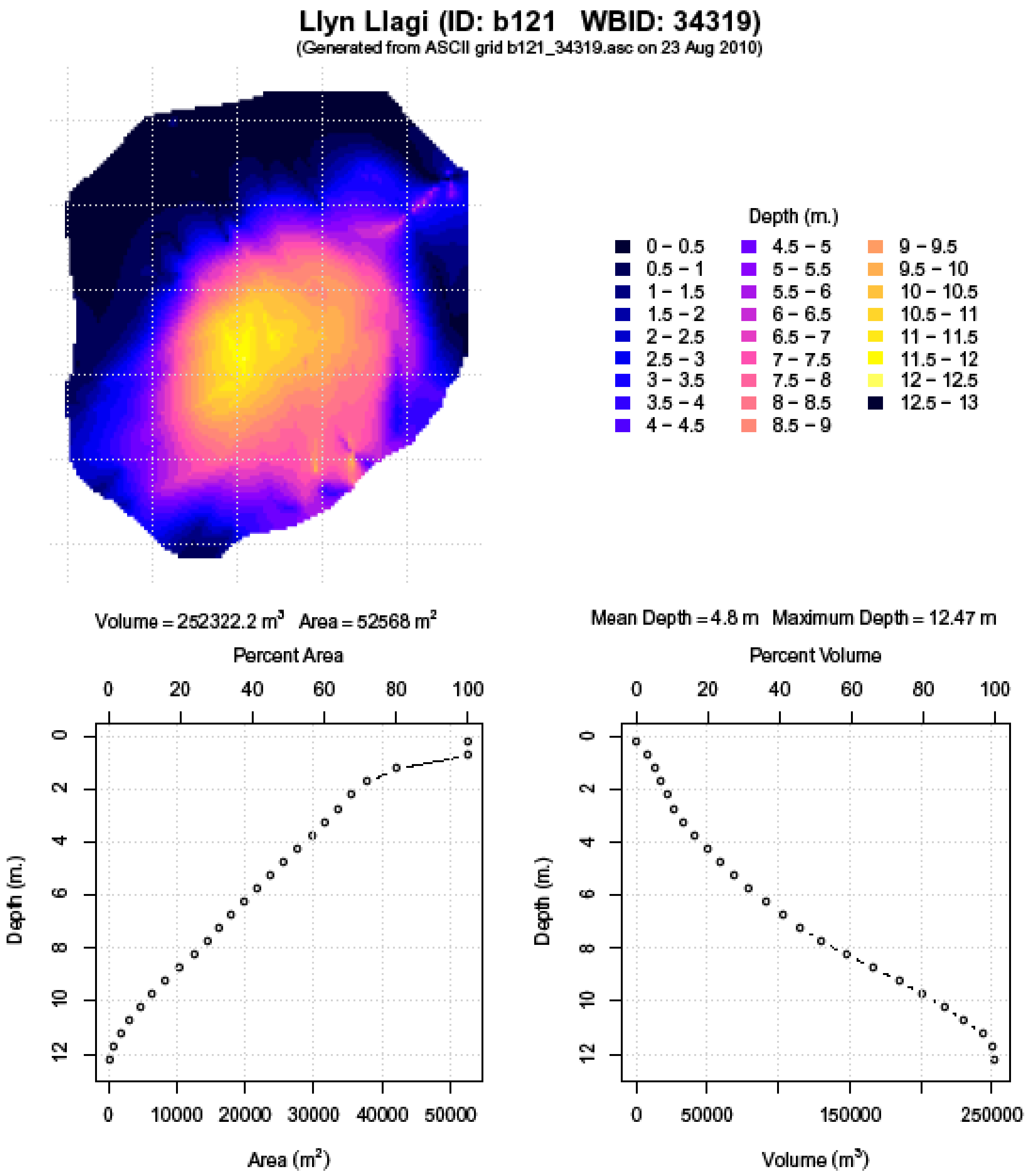


Figure A11.24 R: output compilation figure of Llyn Llagi

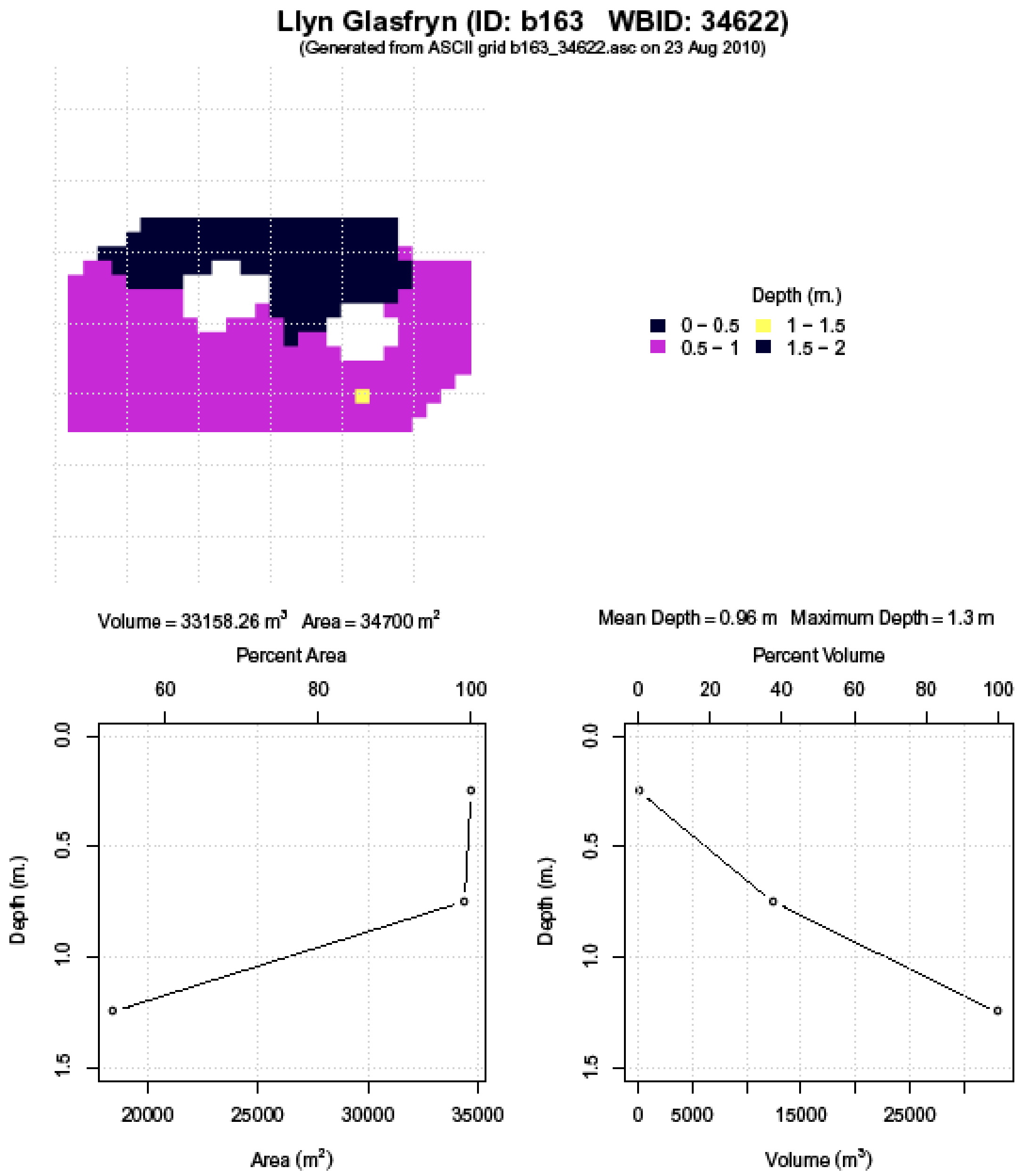


Figure A11.25 R: output compilation figure of Llyn Glasfryn

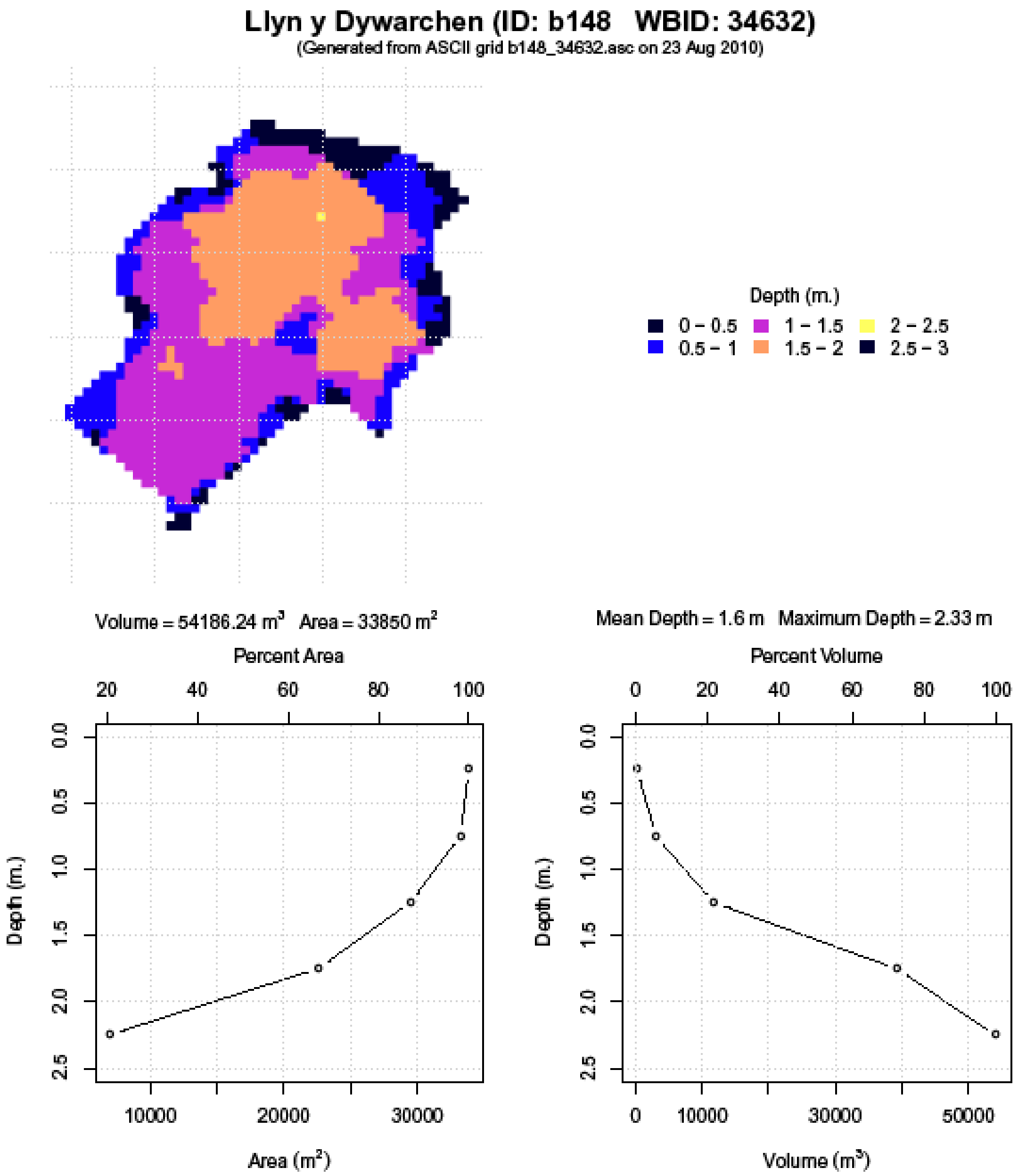


Figure A11.26 R: output compilation figure of Llyn y Dywarchen

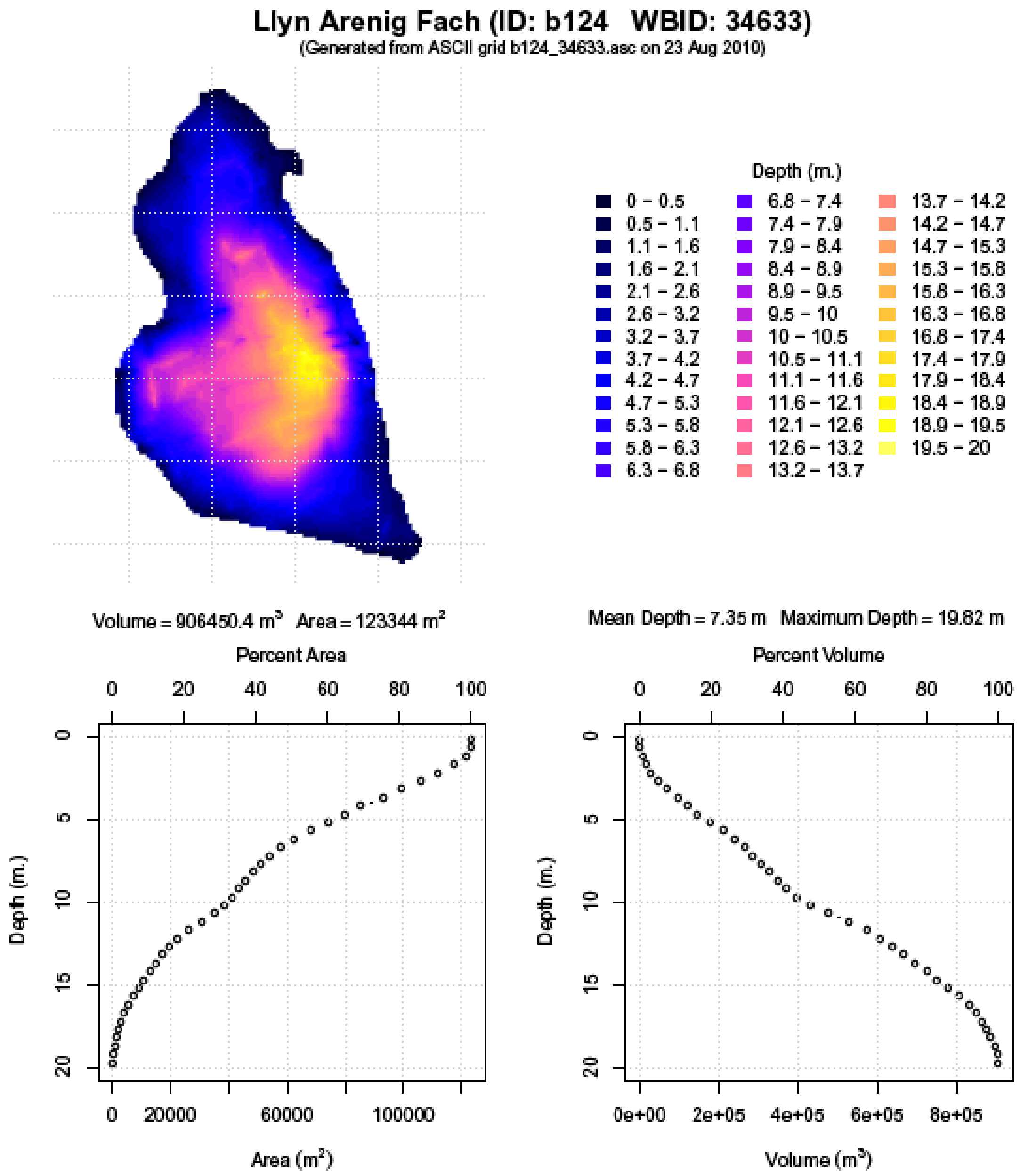


Figure A11.27 R: output compilation figure of Llyn Arenig Fach

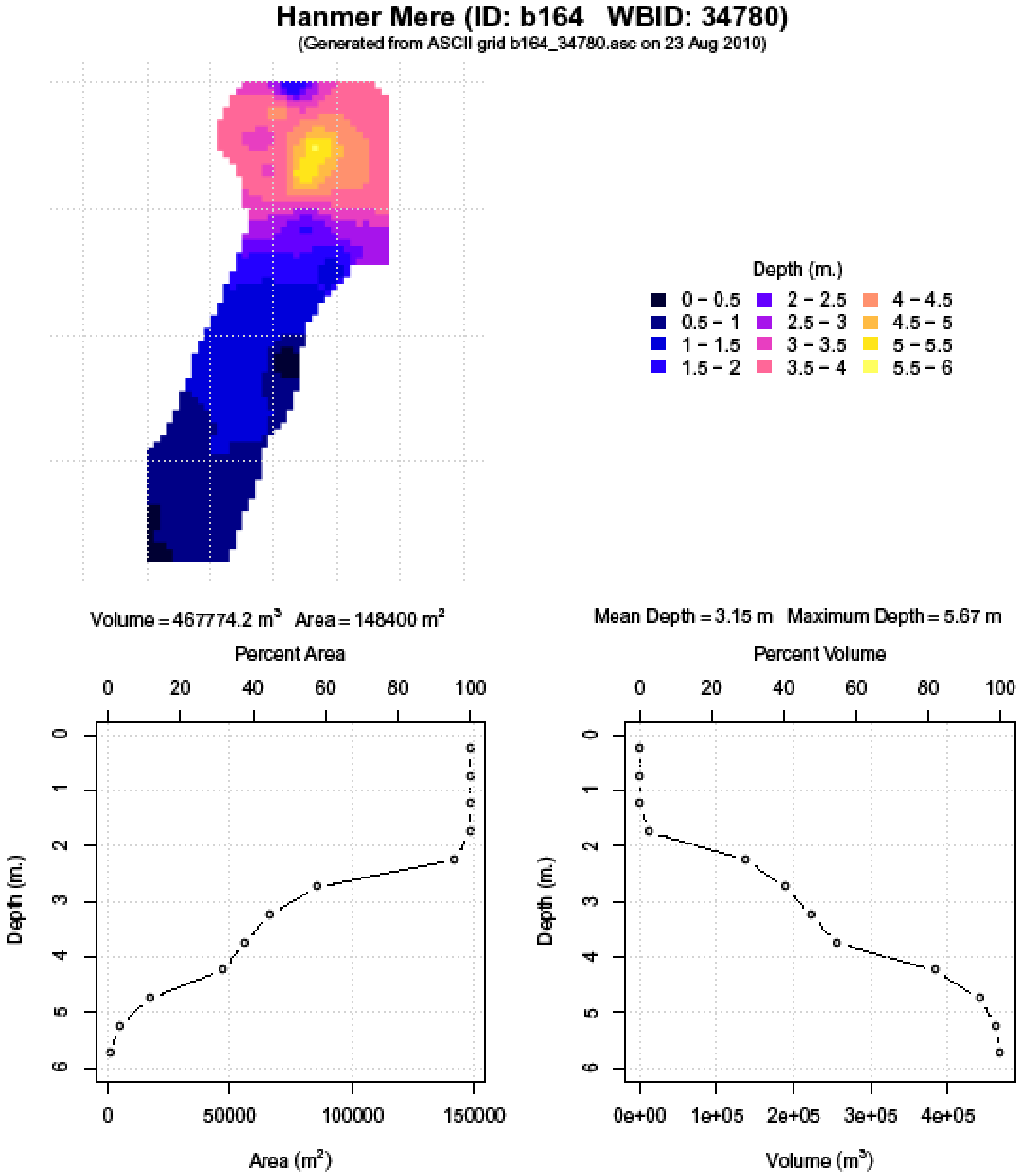


Figure A11.28 R: output compilation figure of Hanmer Mere

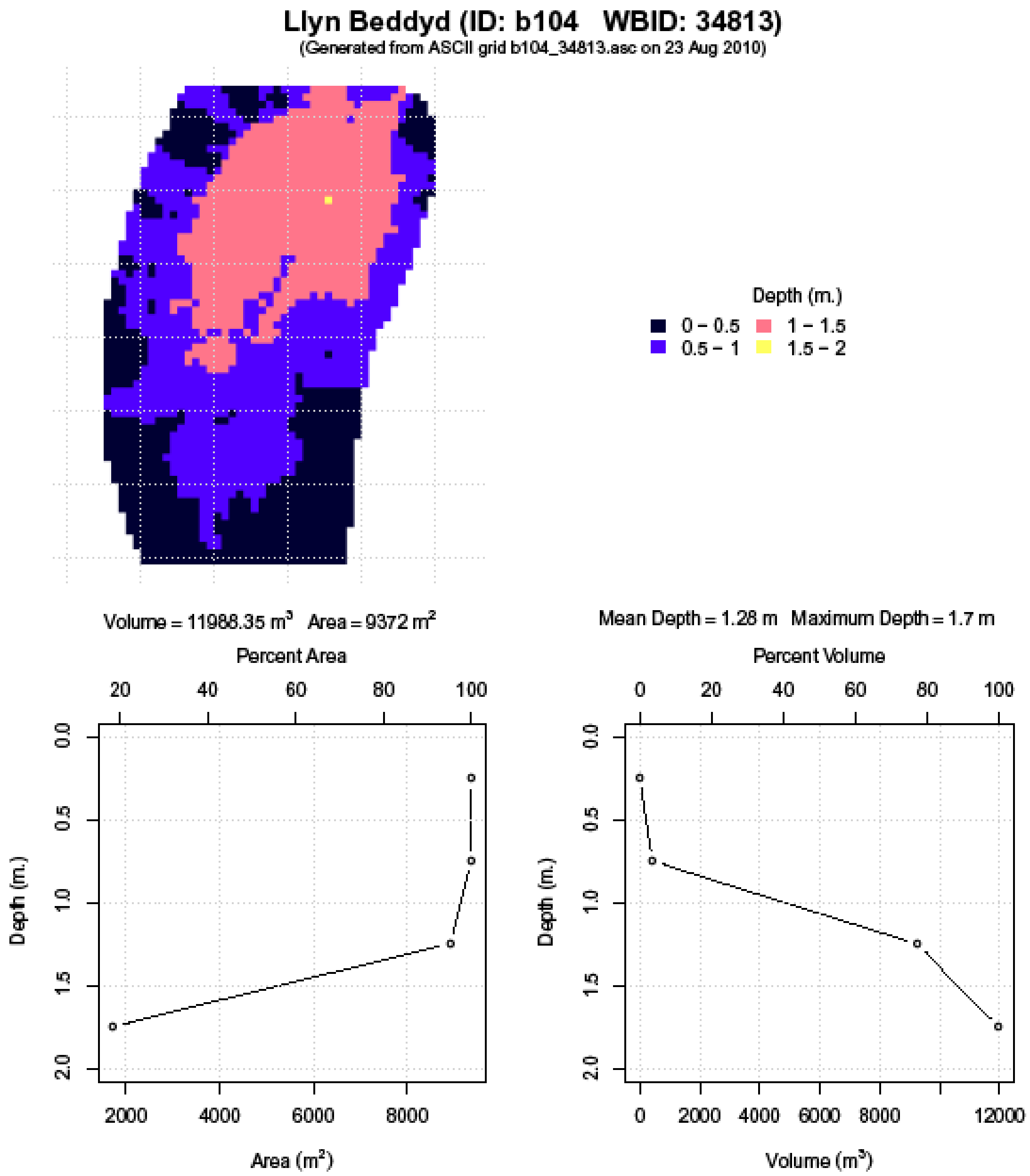


Figure A11.29 R: output compilation figure of Llyn Beddyd

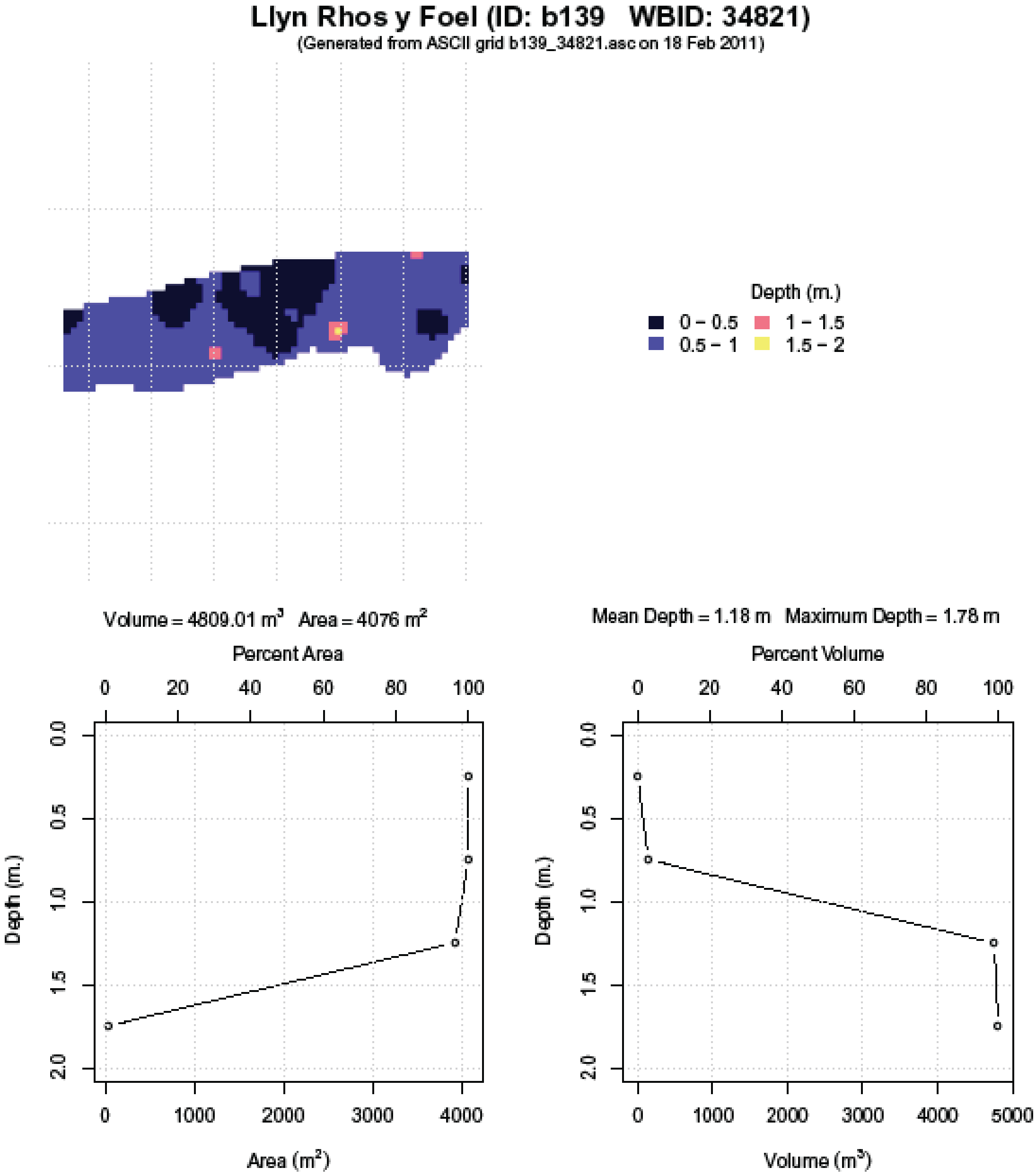


Figure A11.30 R: output compilation figure of Llyn Rhos y Foel

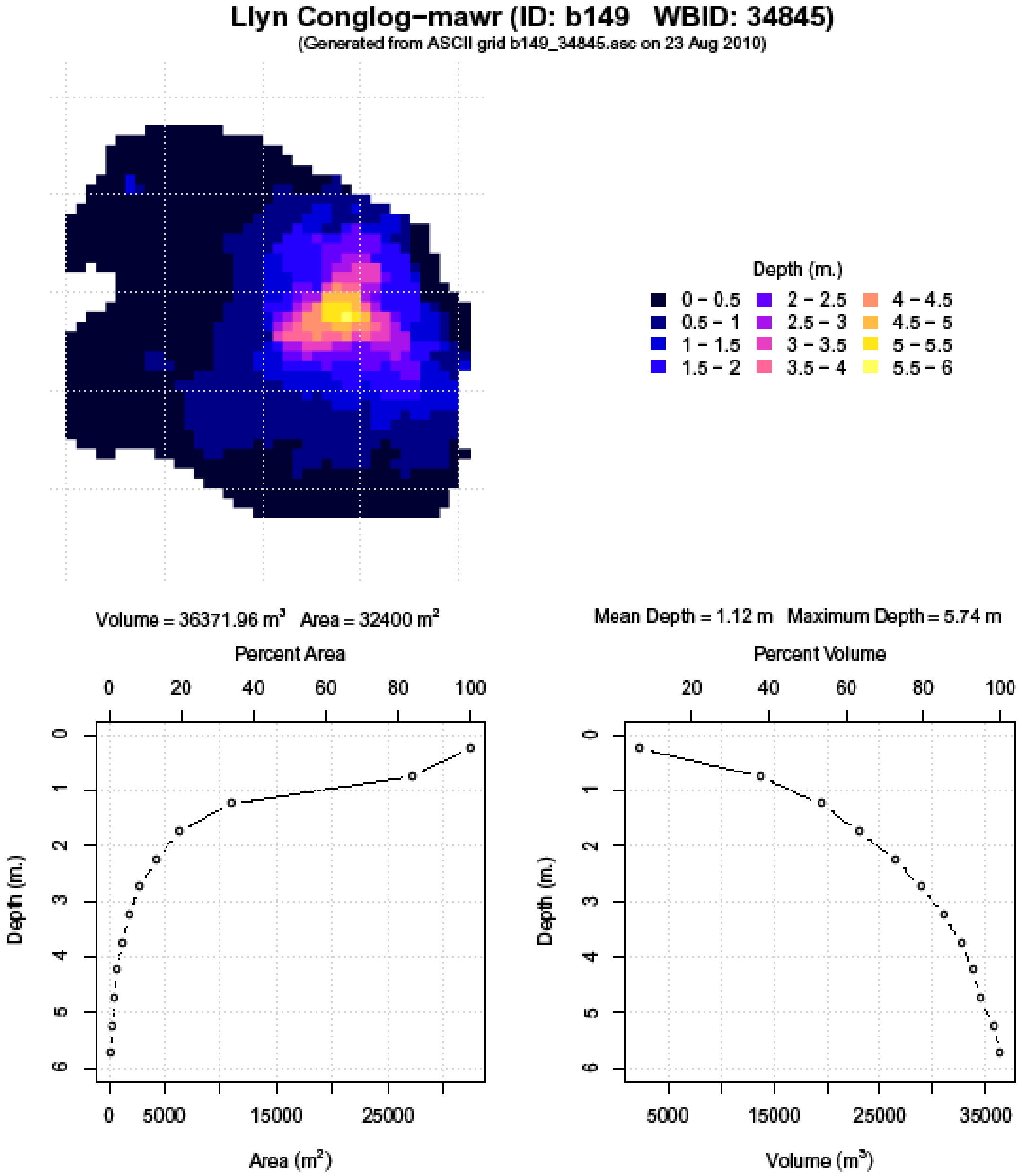


Figure A11.31 R: output compilation figure of Llyn Conglog-mawr

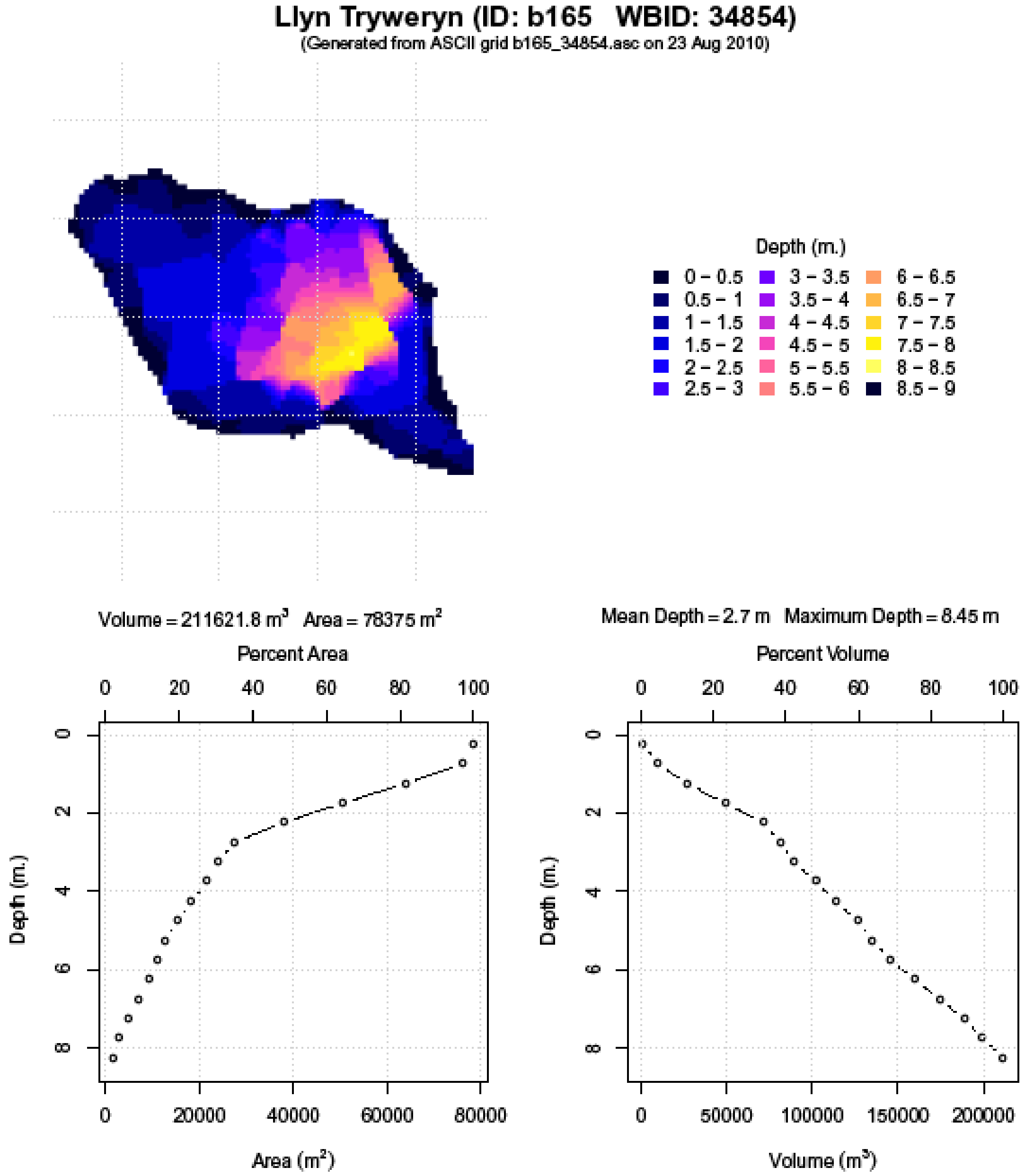


Figure A11.32 R: output compilation figure of Llyn Tryweryn

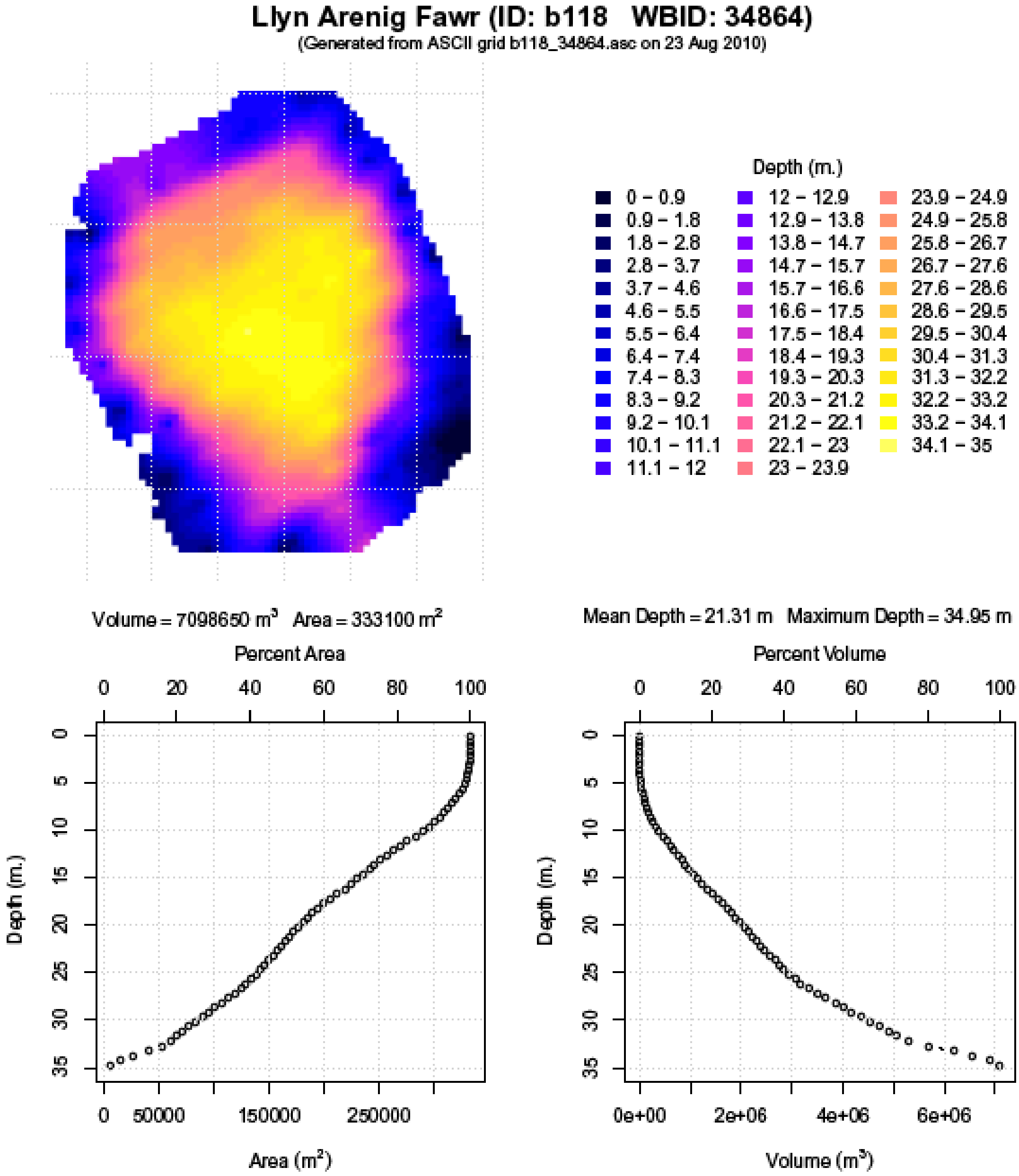


Figure A11.33 R: output compilation figure of Llyn Arenig Fawr

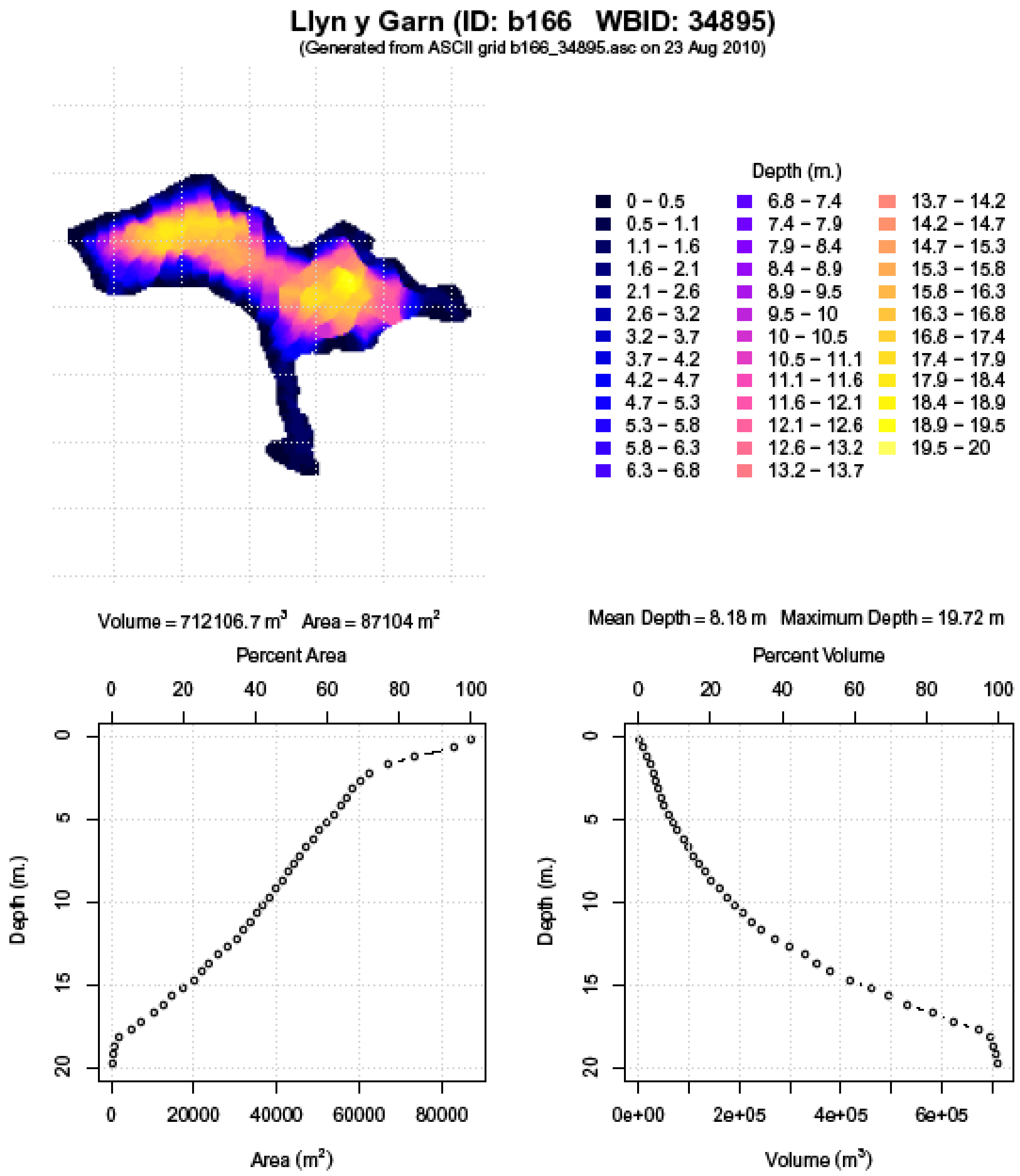


Figure A11.34 R: output compilation figure of Llyn y Garn

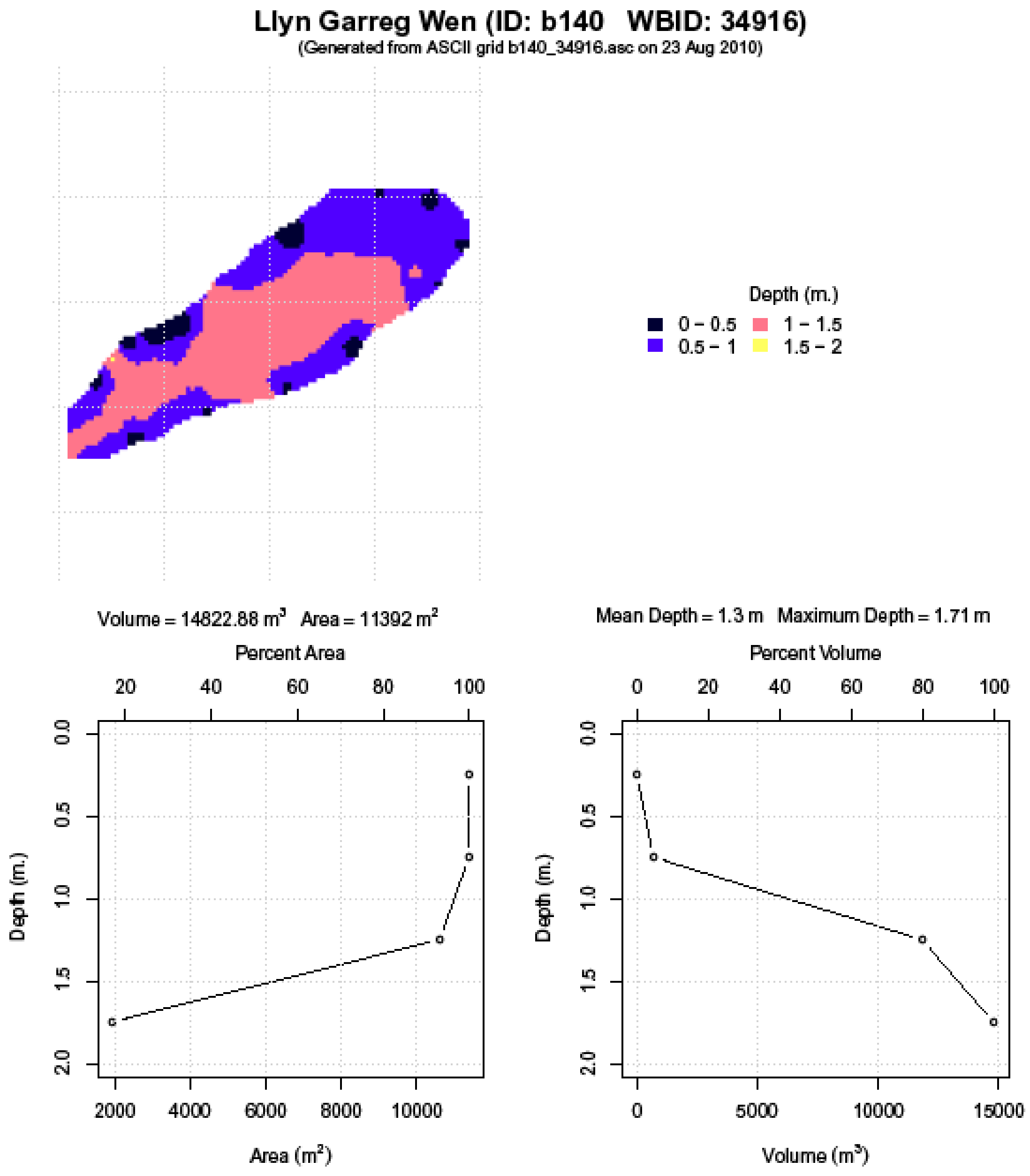


Figure A11.35 R: output compilation figure of Llyn Garreg Wen

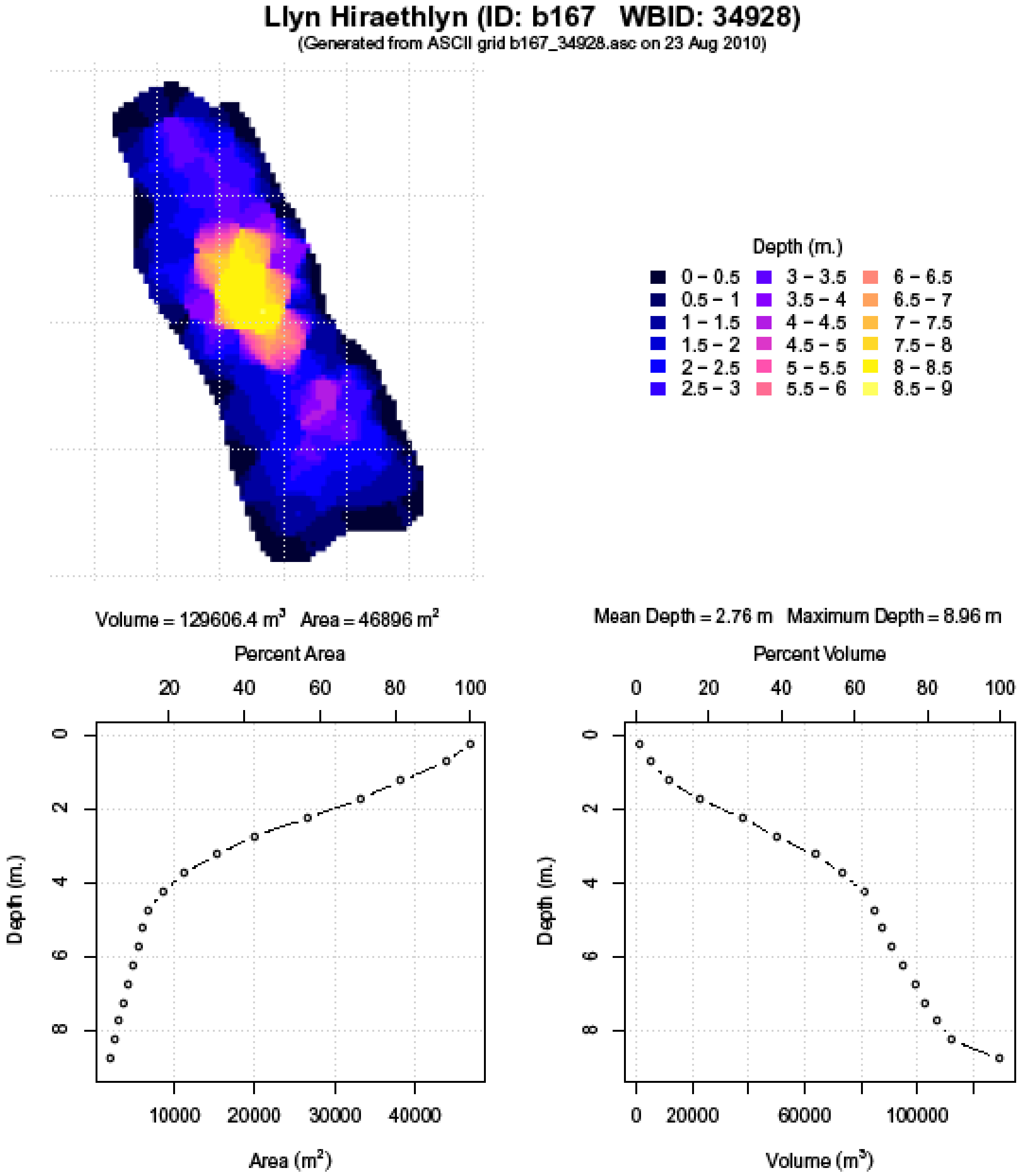


Figure A11.36 R: output compilation figure of Llyn Hiraethlyn

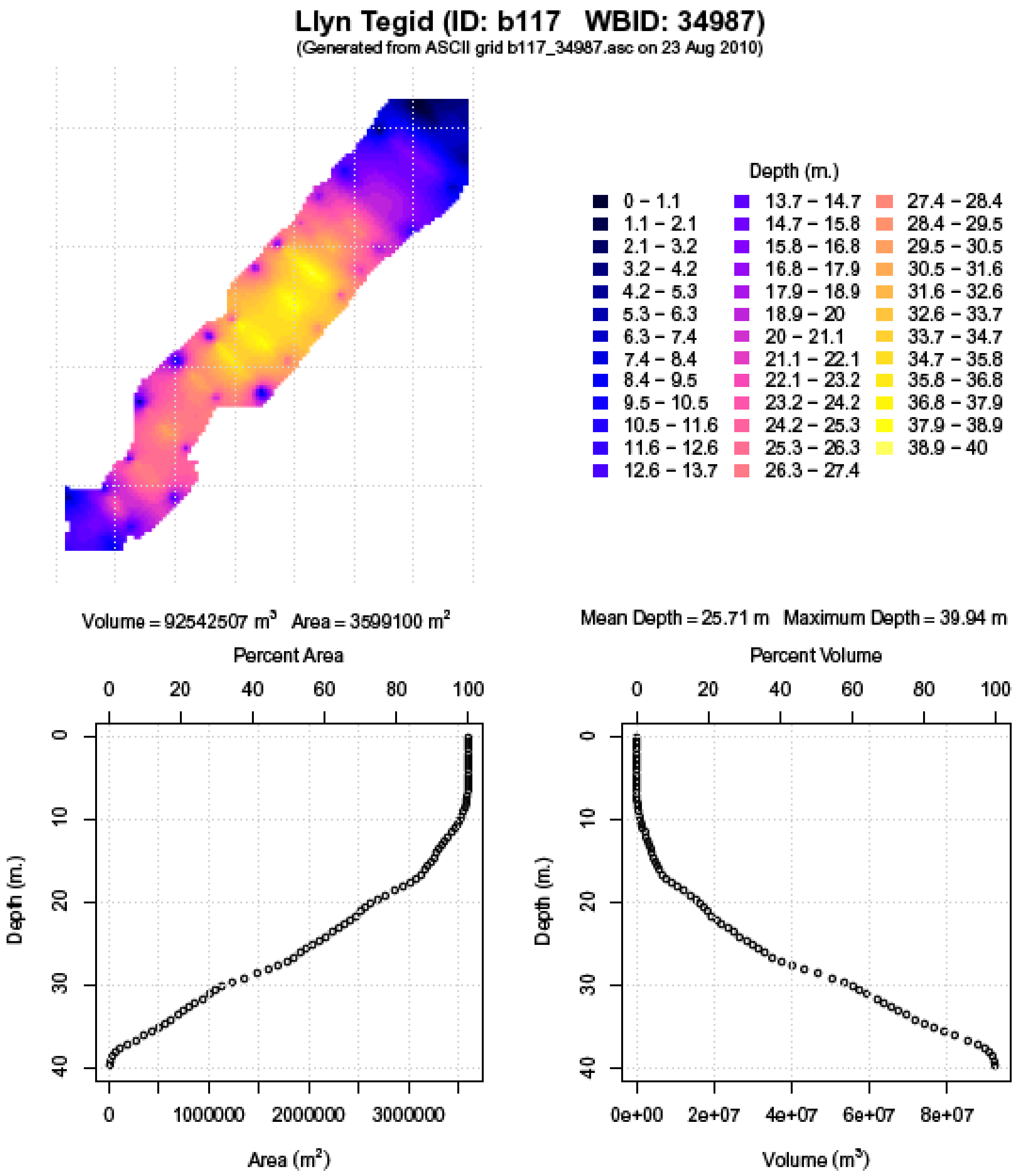


Figure A11.37 R: output compilation figure of Llyn Tegid

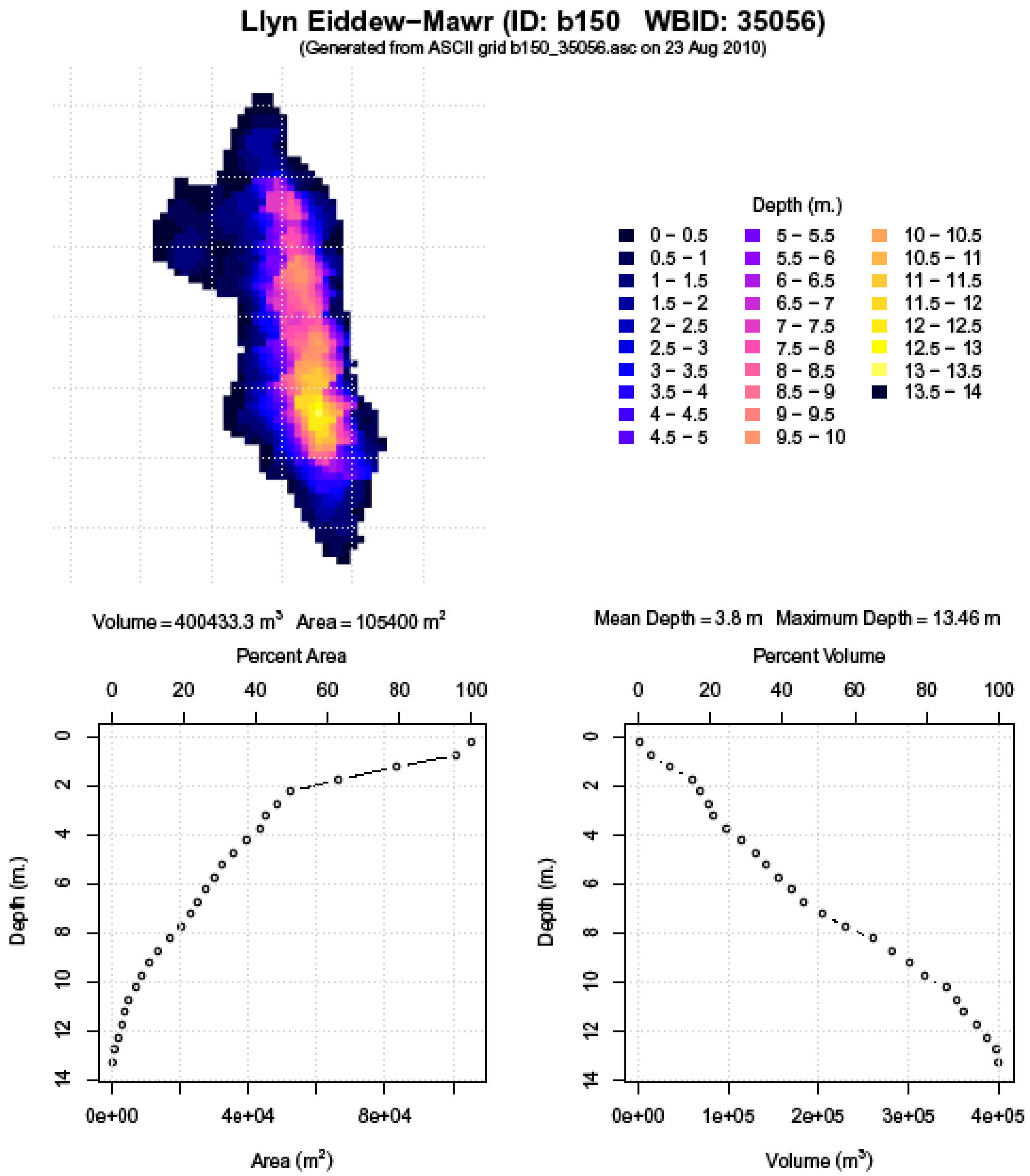


Figure A11.38 R: output compilation figure of Llyn Eiddew-Mawr

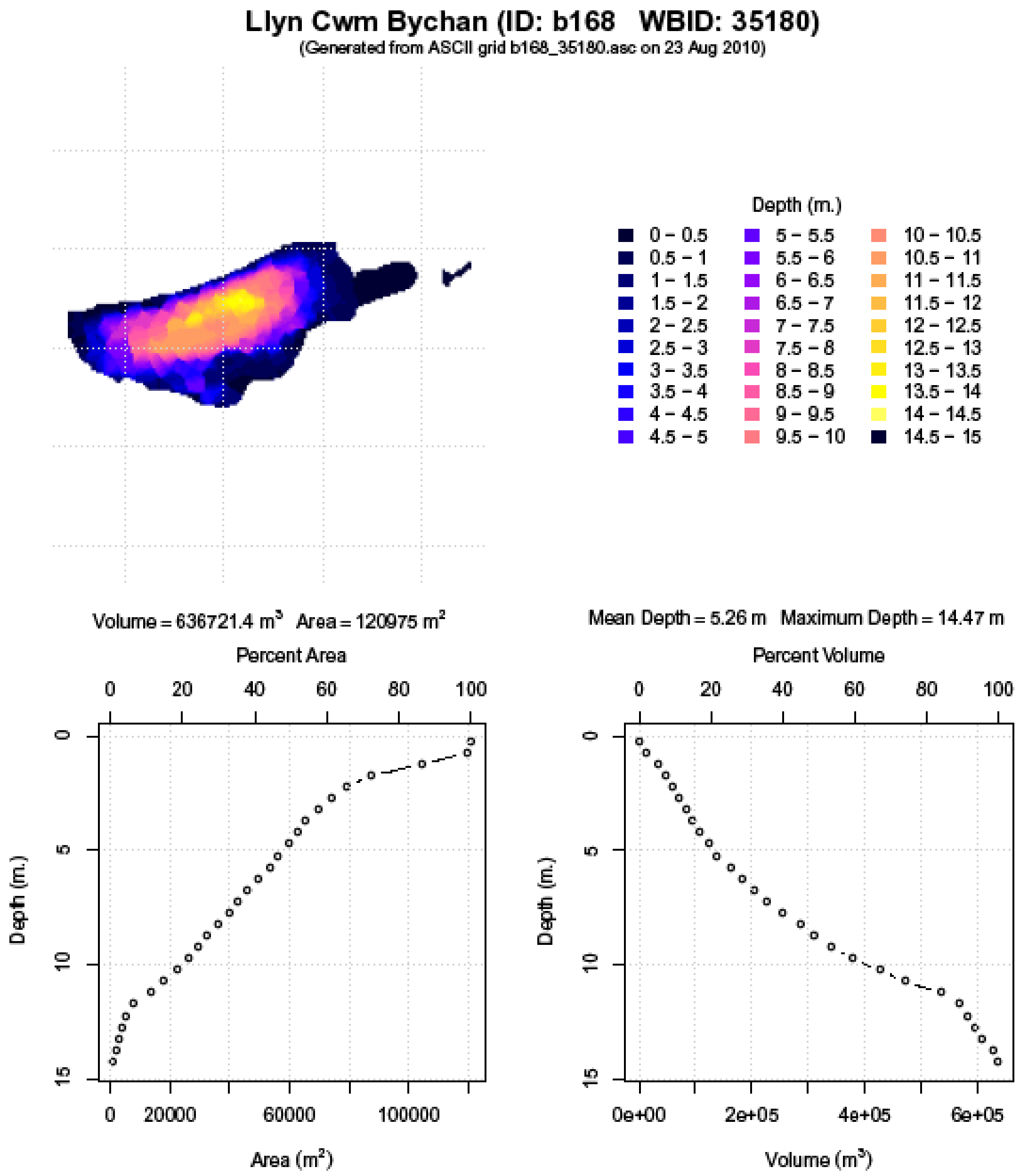


Figure A11.39 R: output compilation figure of Llyn Cwm Bychan

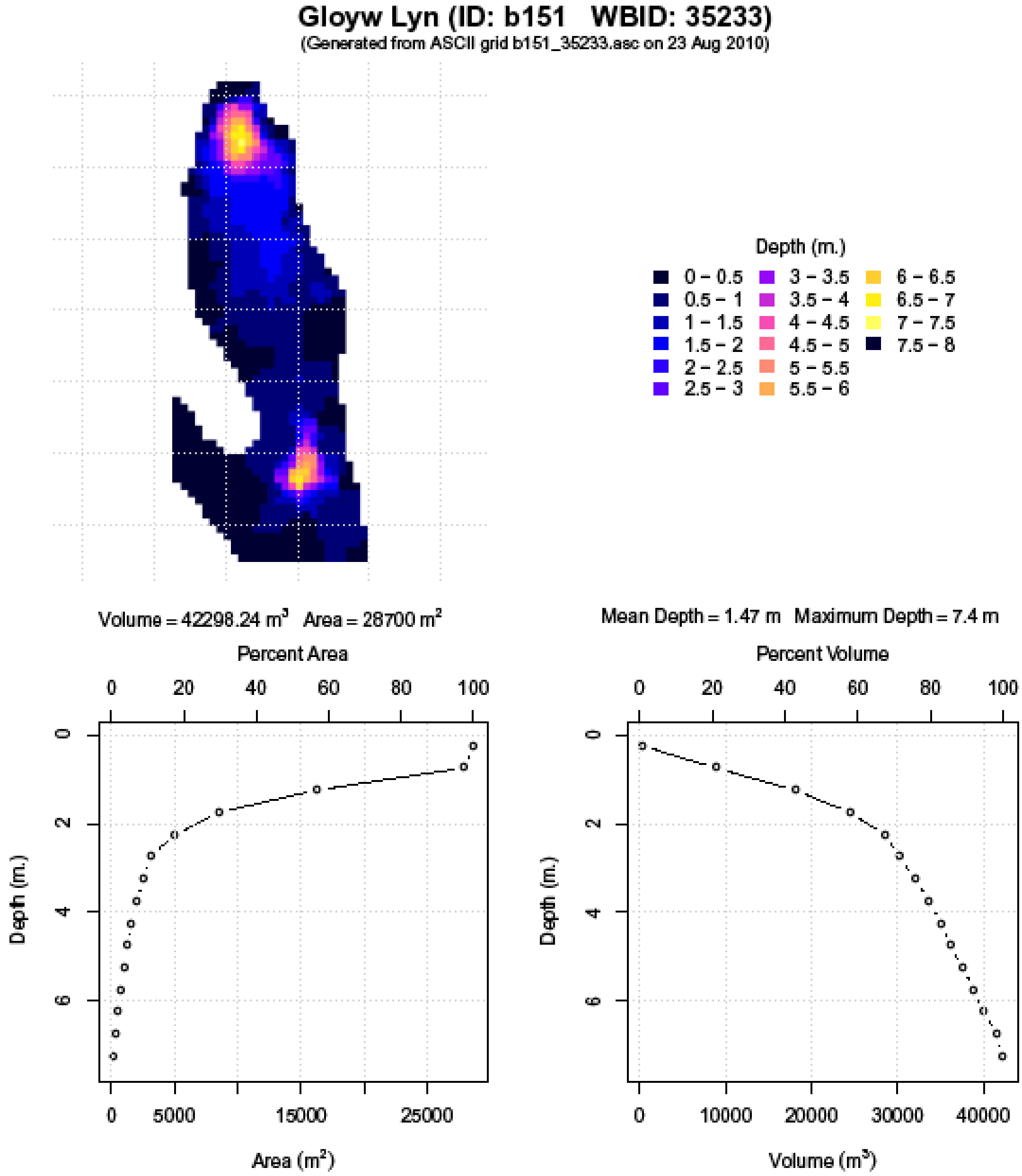


Figure A11.40 R: output compilation figure of Gloyw Lyn

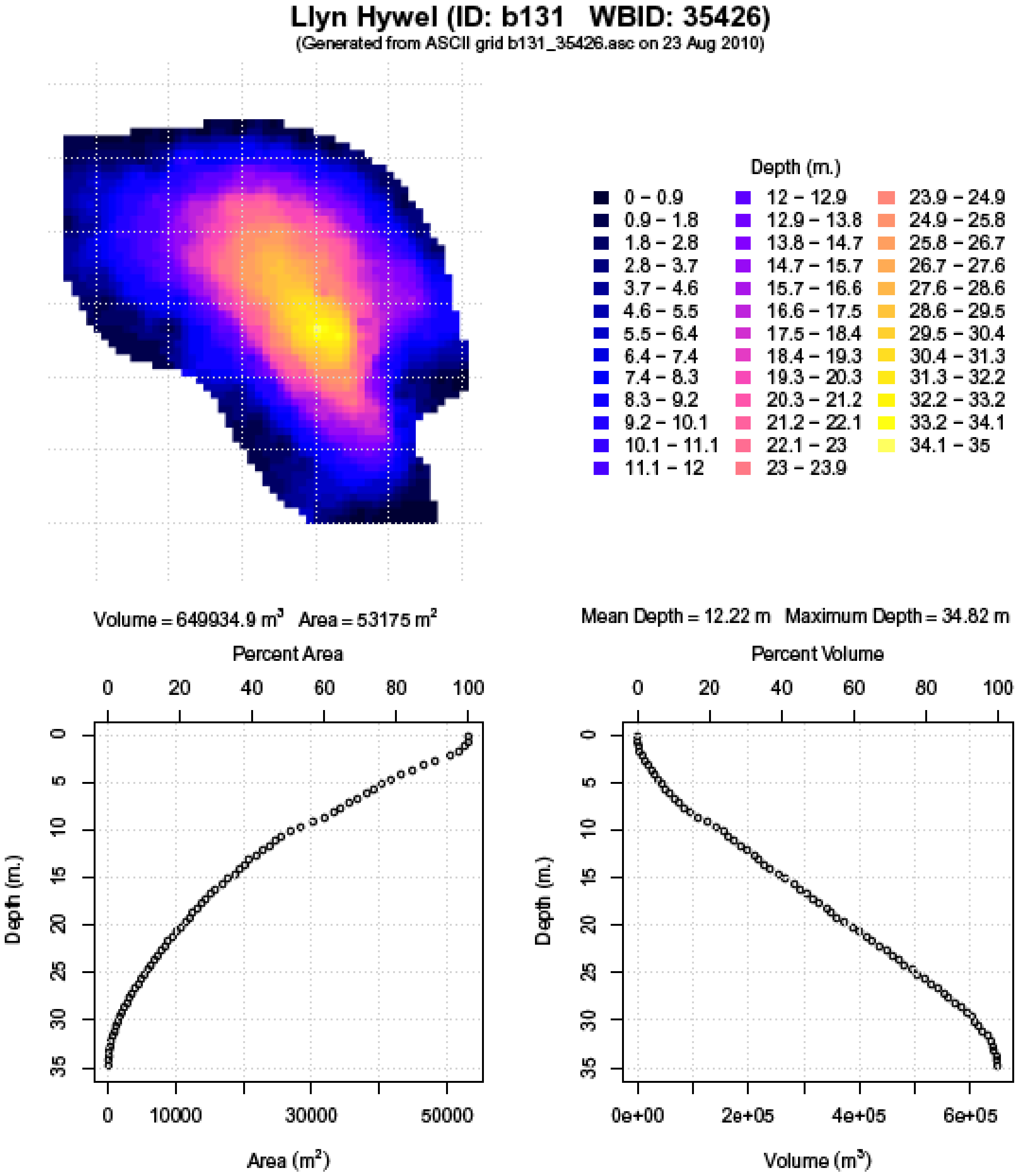


Figure A11.41 R: output compilation figure of Llyn Hywel

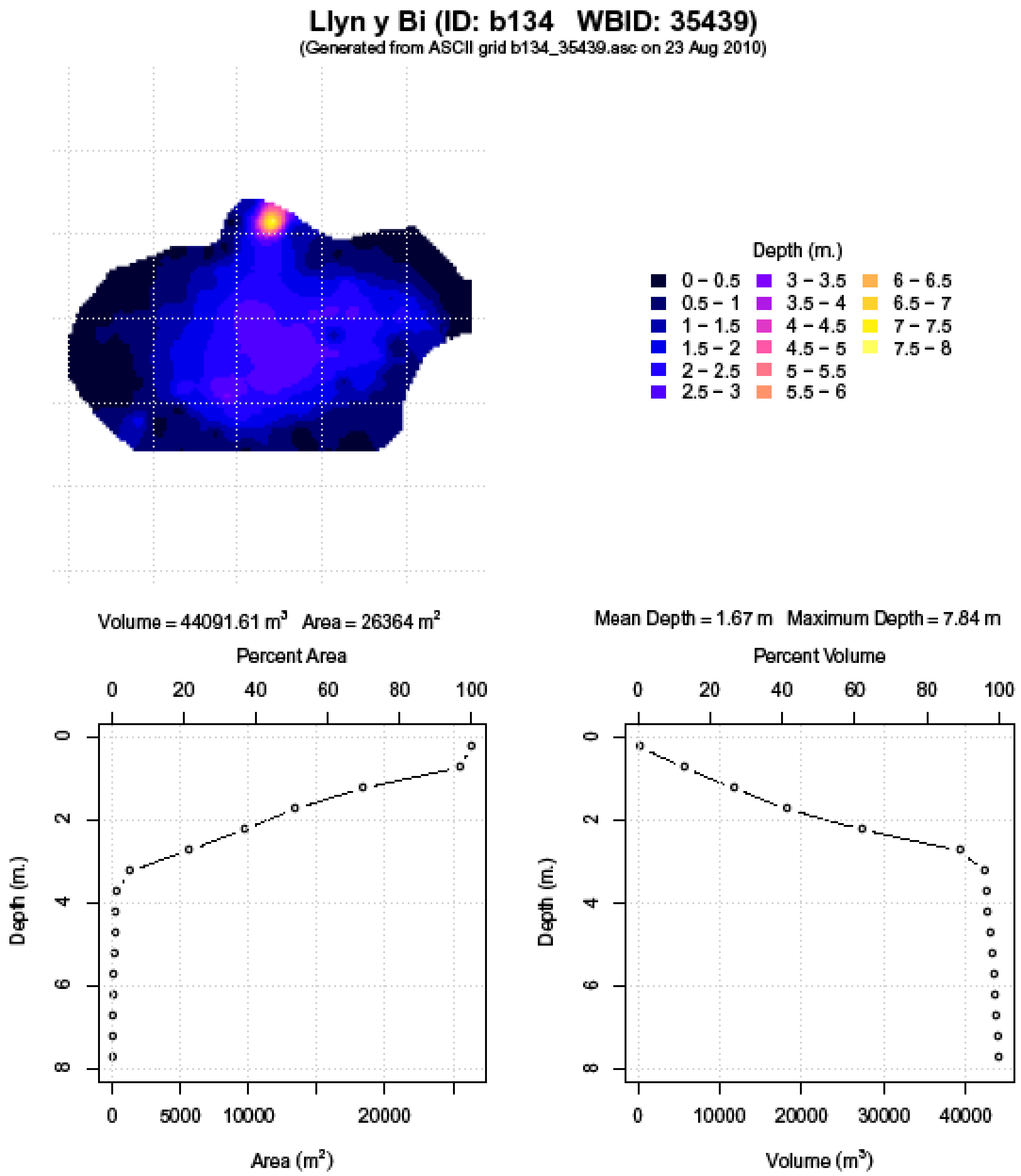


Figure A11.42 R: output compilation figure of Llyn y Bi

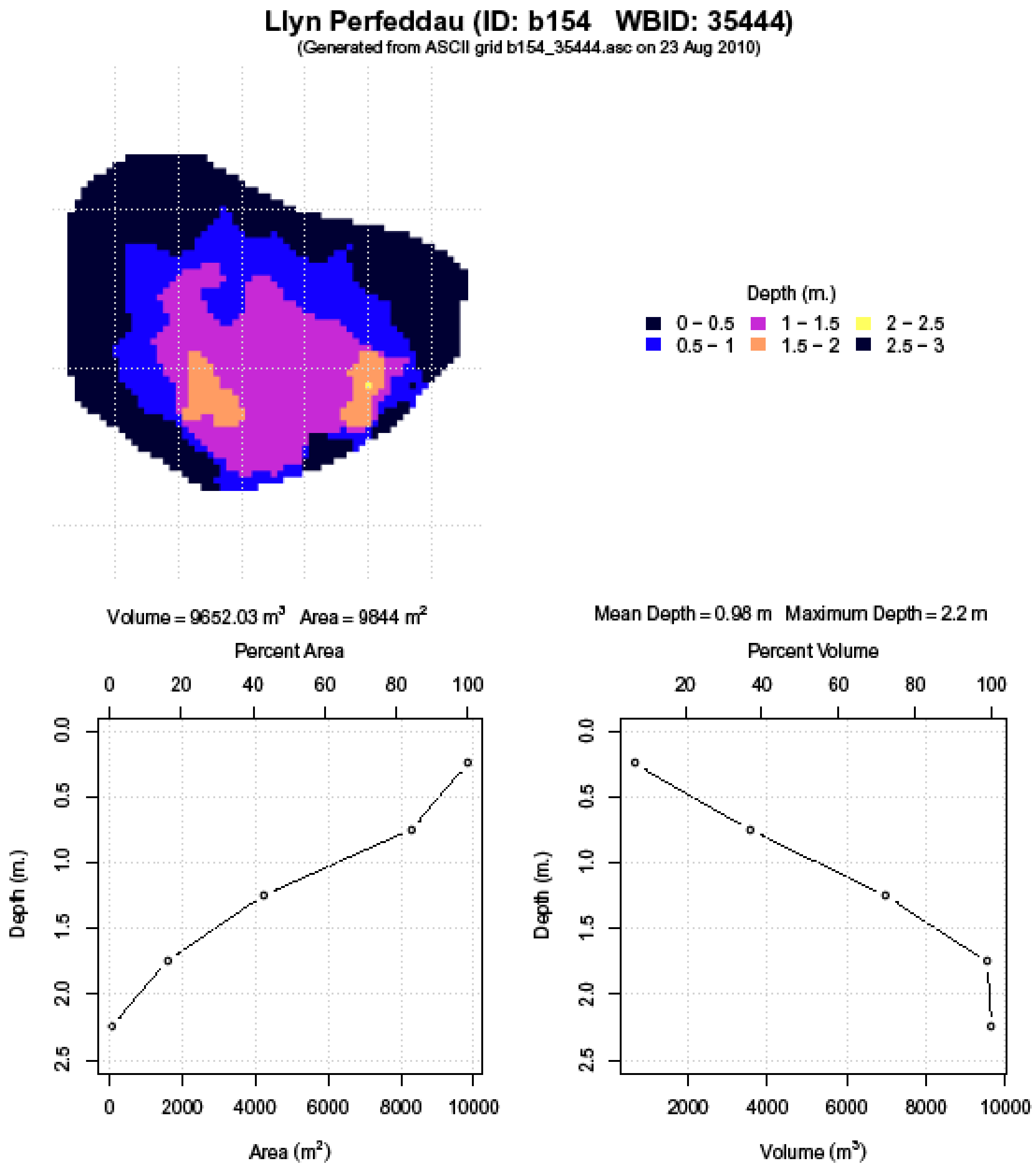


Figure A11.43 R: output compilation figure of Llyn Perfeddau

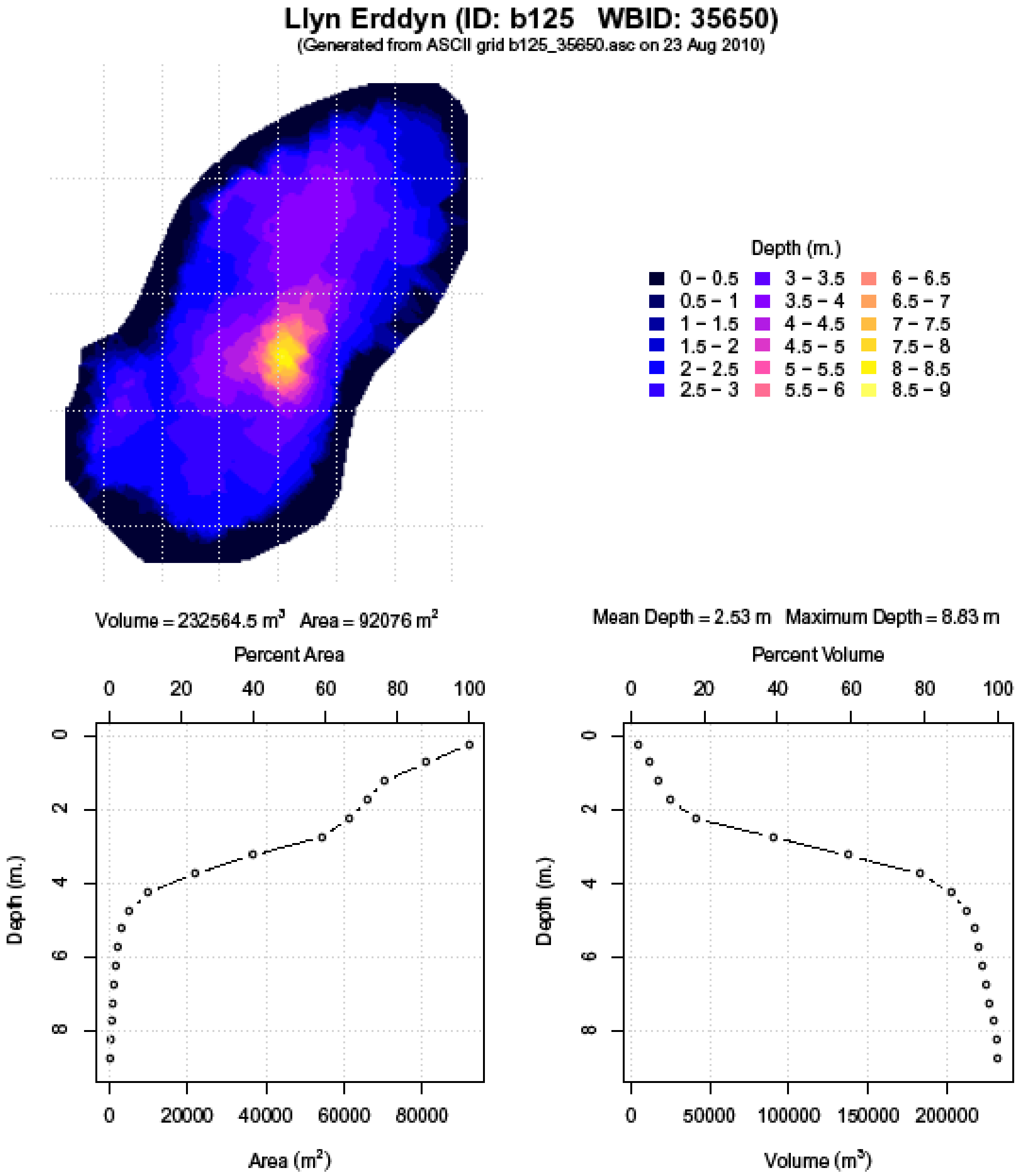


Figure A11.44 R: output compilation figure of Llyn Erddyn

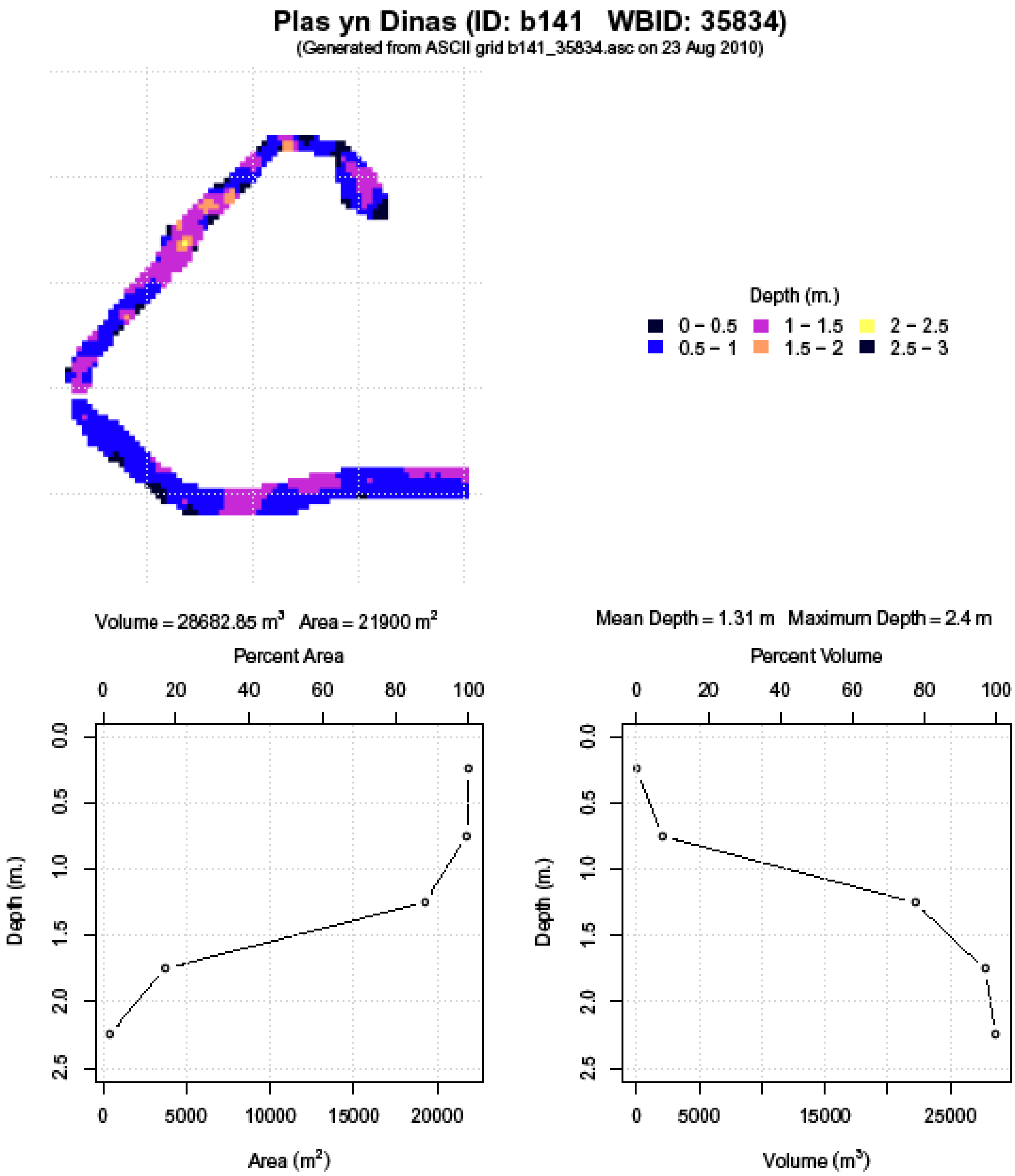


Figure A11.45 R: output compilation figure of Plas yn Dinas

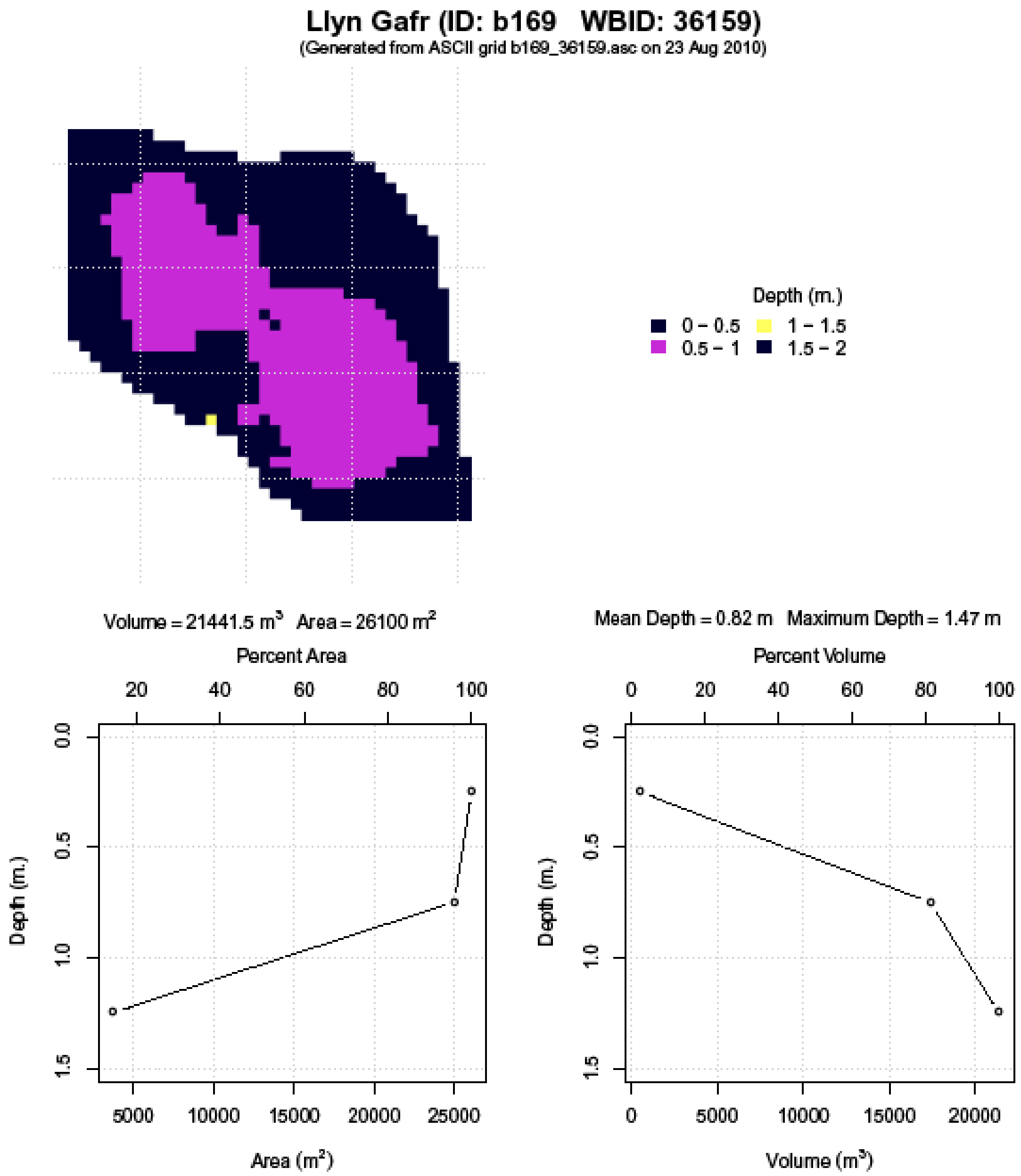


Figure A11.46 R: output compilation figure of Llyn Gafr

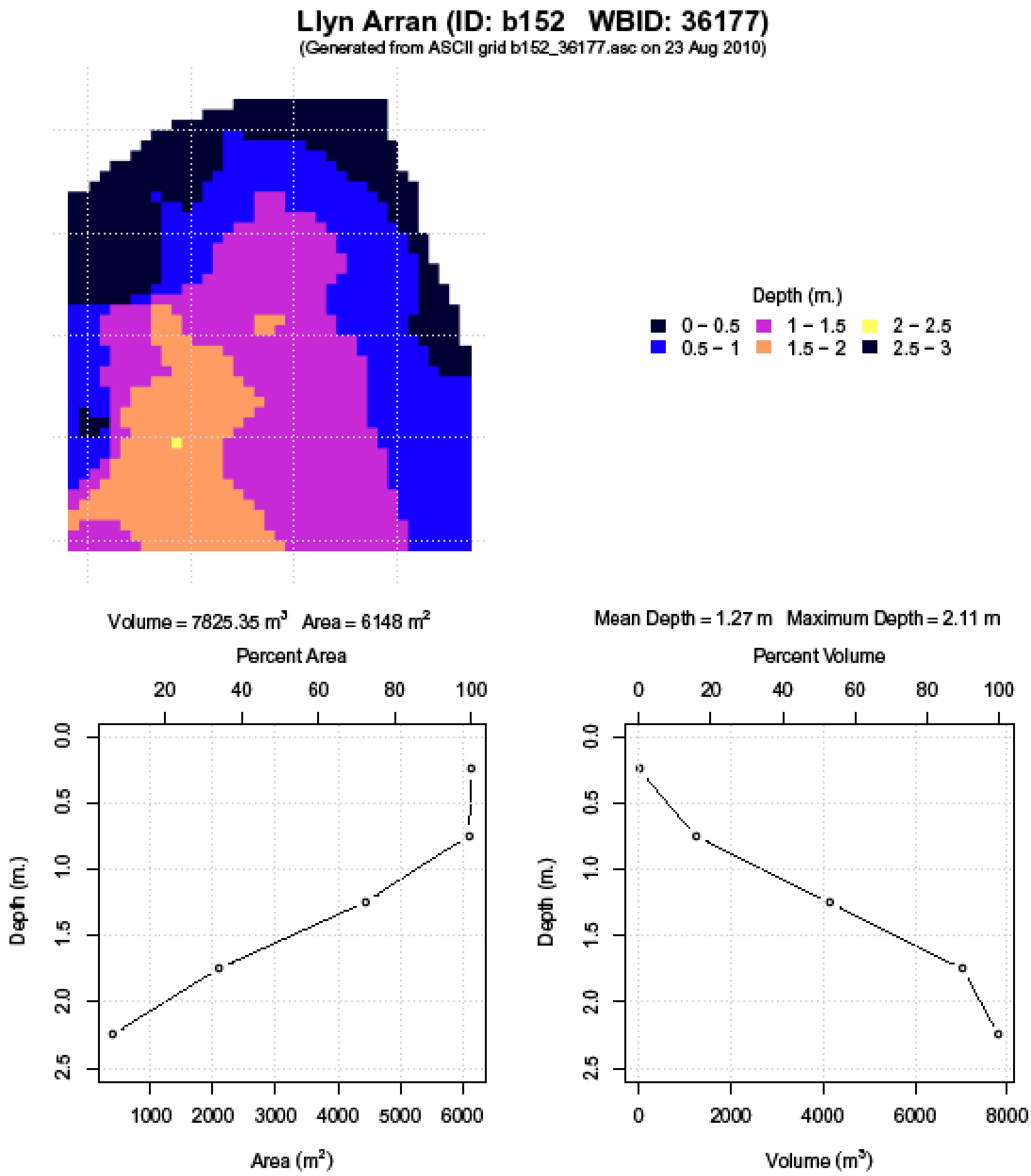


Figure A11.47 R: output compilation figure of Llyn Arran

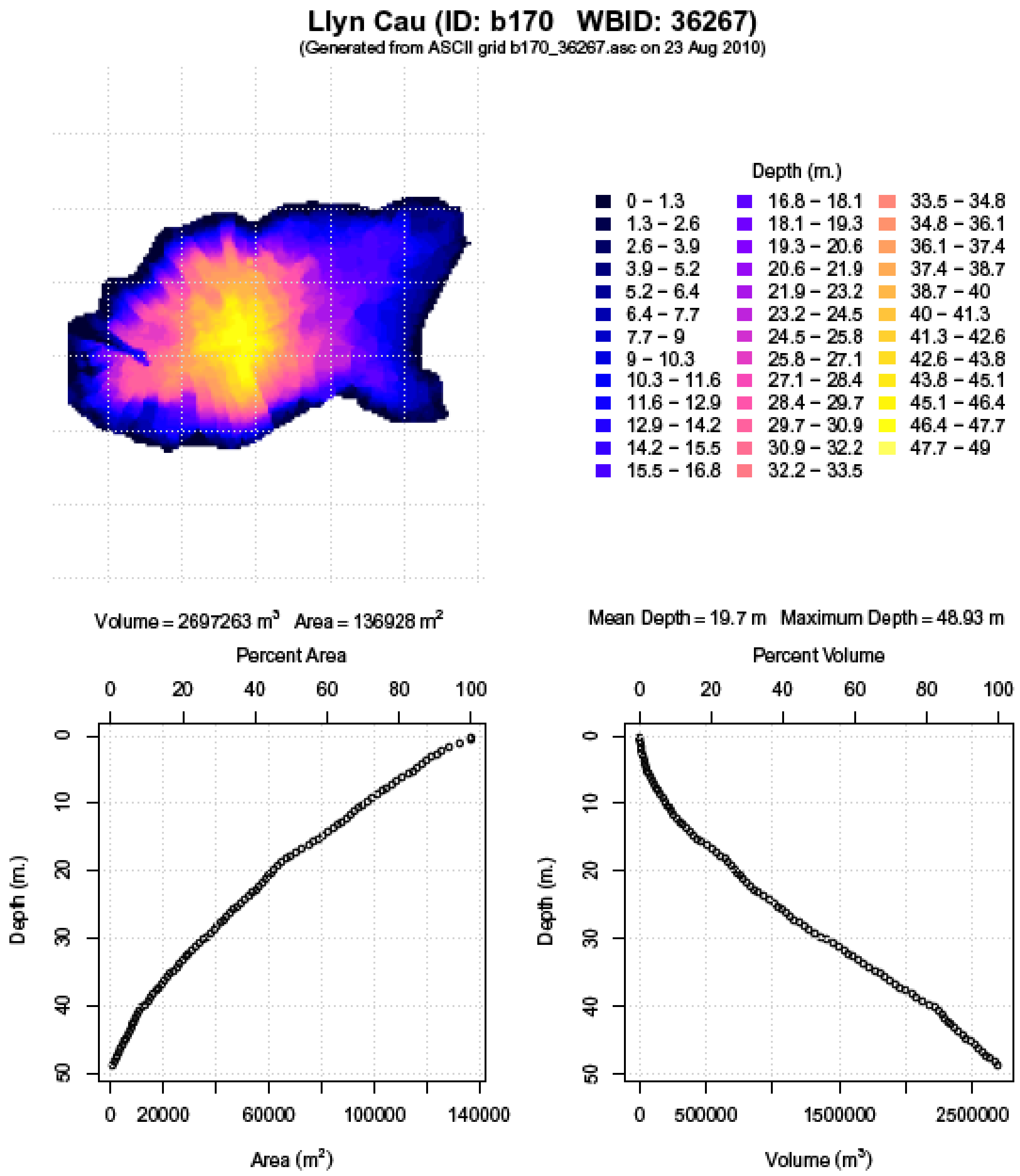


Figure A11.48 R: output compilation figure of Llyn Cau

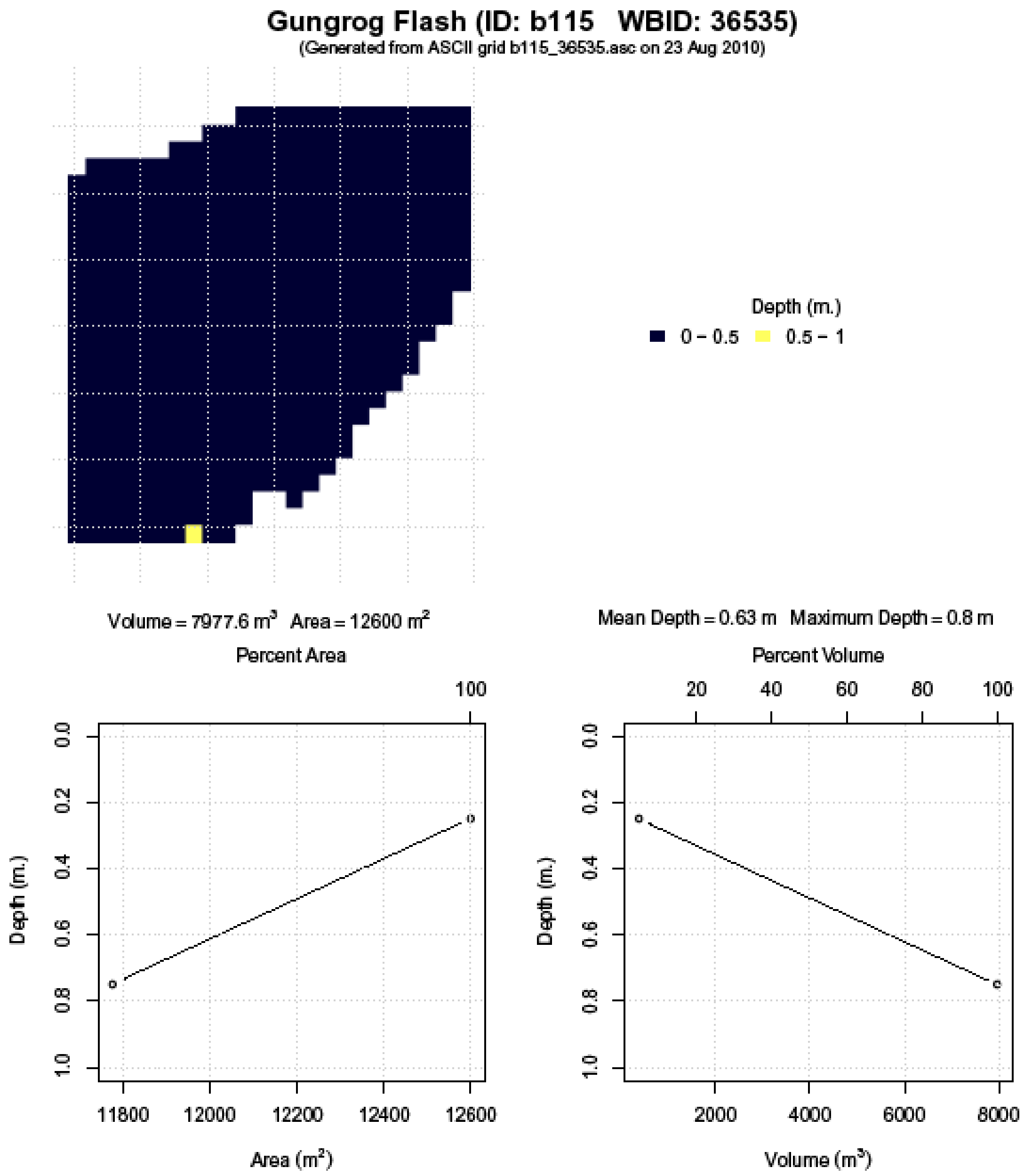


Figure A11.49 R: output compilation figure of Gungrog Flash

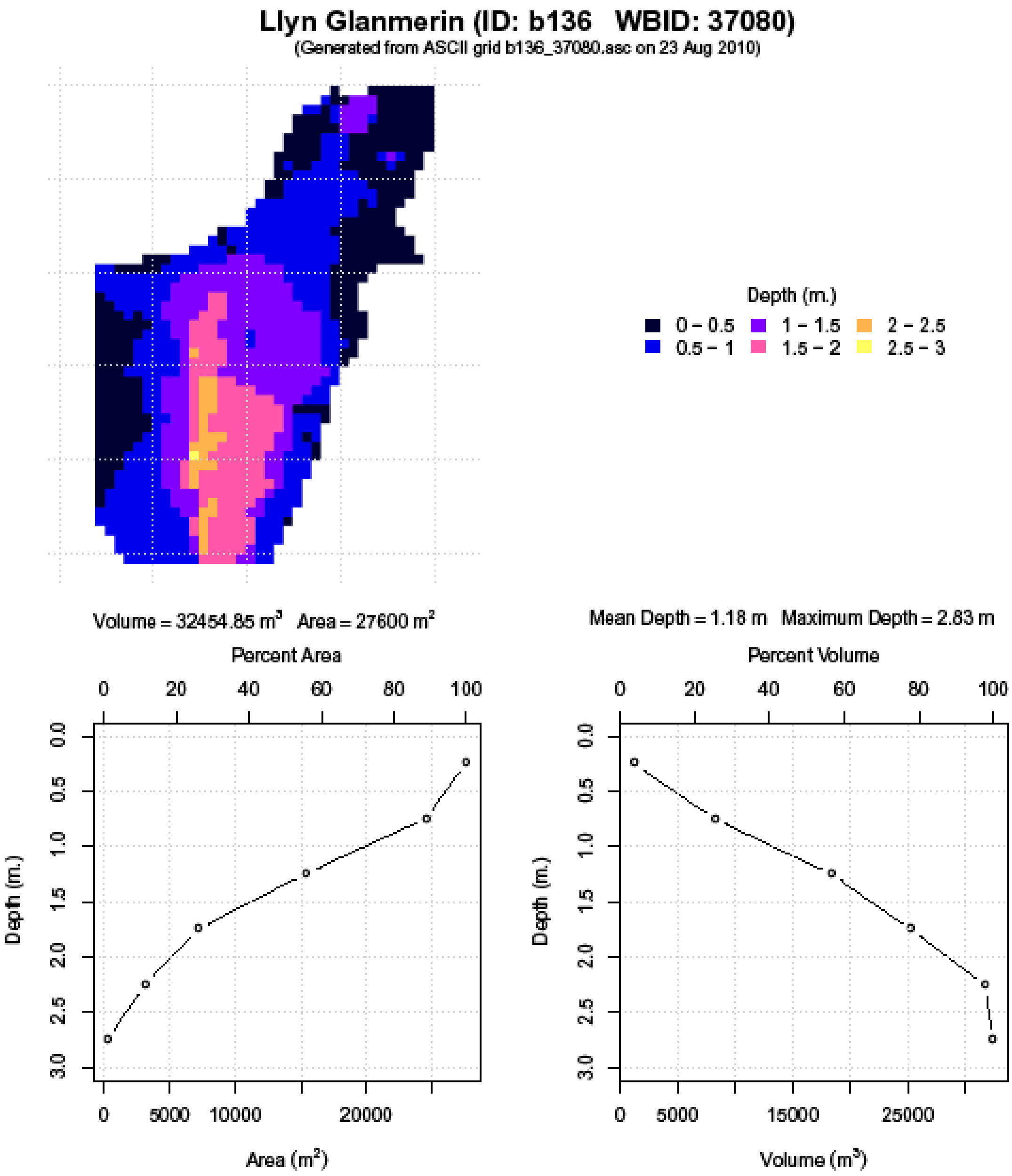


Figure A11.50 R: output compilation figure of Llyn Glanmerin

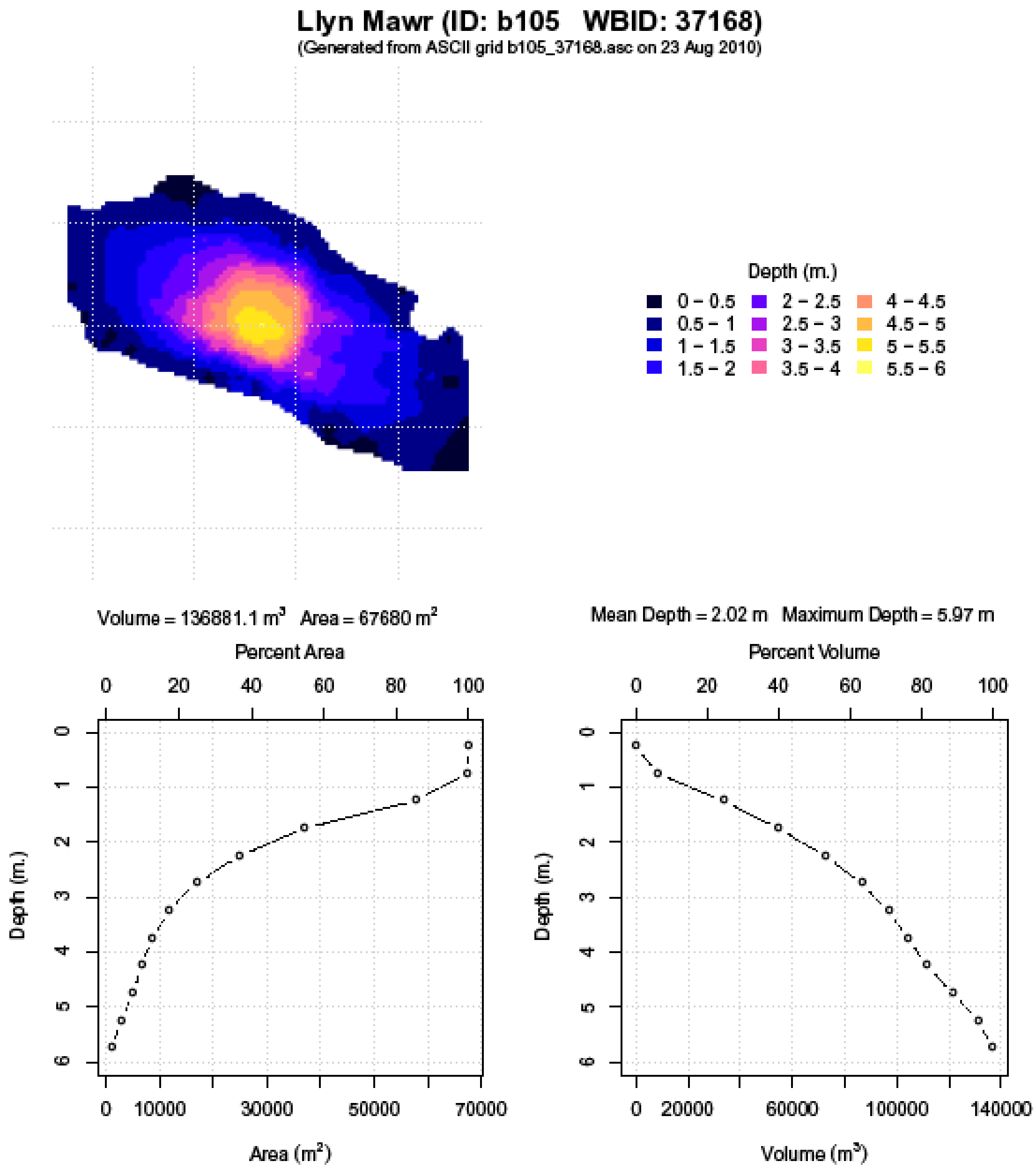


Figure A11.51 R: output compilation figure of Llyn Mawr

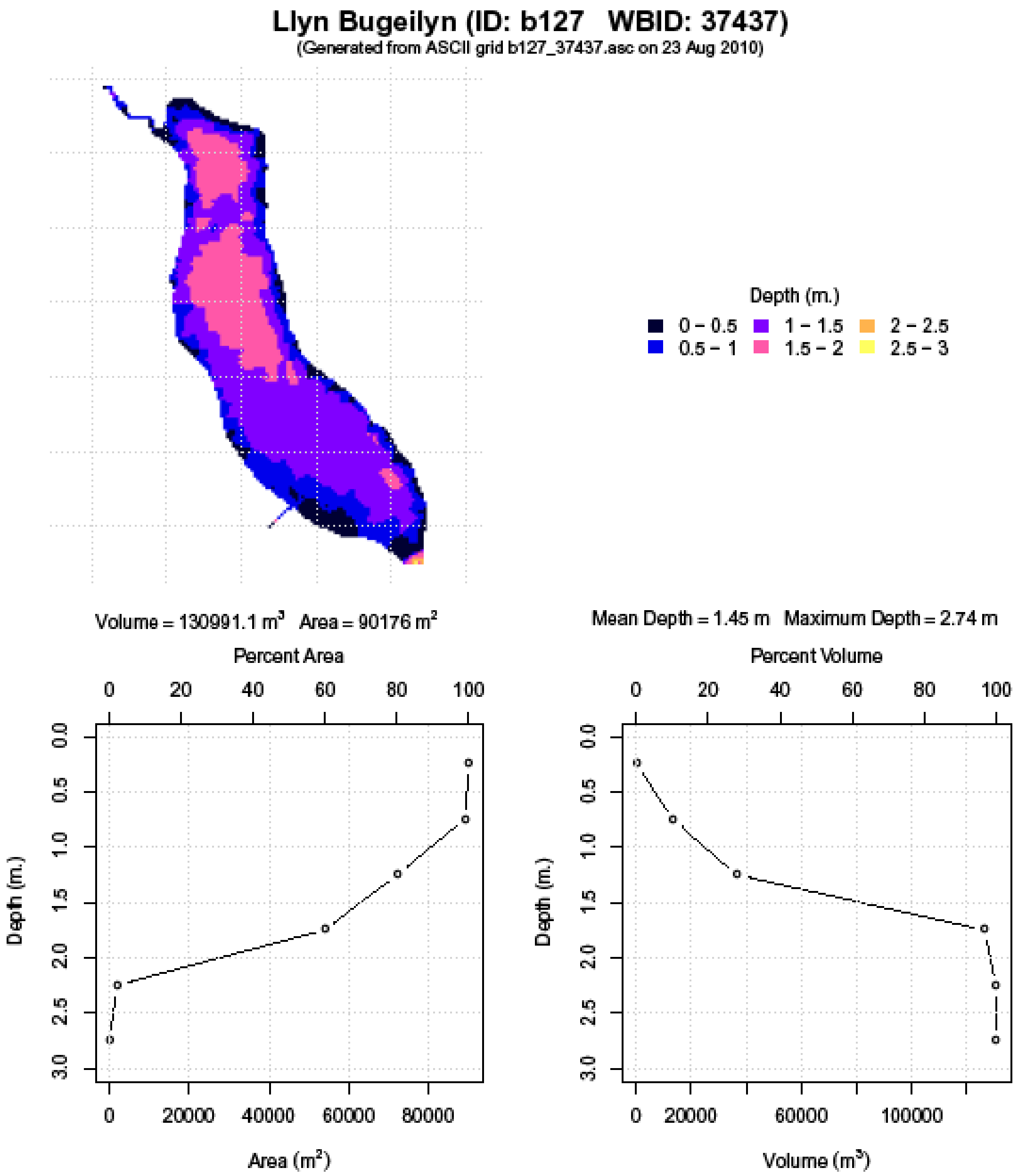


Figure A11.52 R: output compilation figure of Llyn Bugeilyn

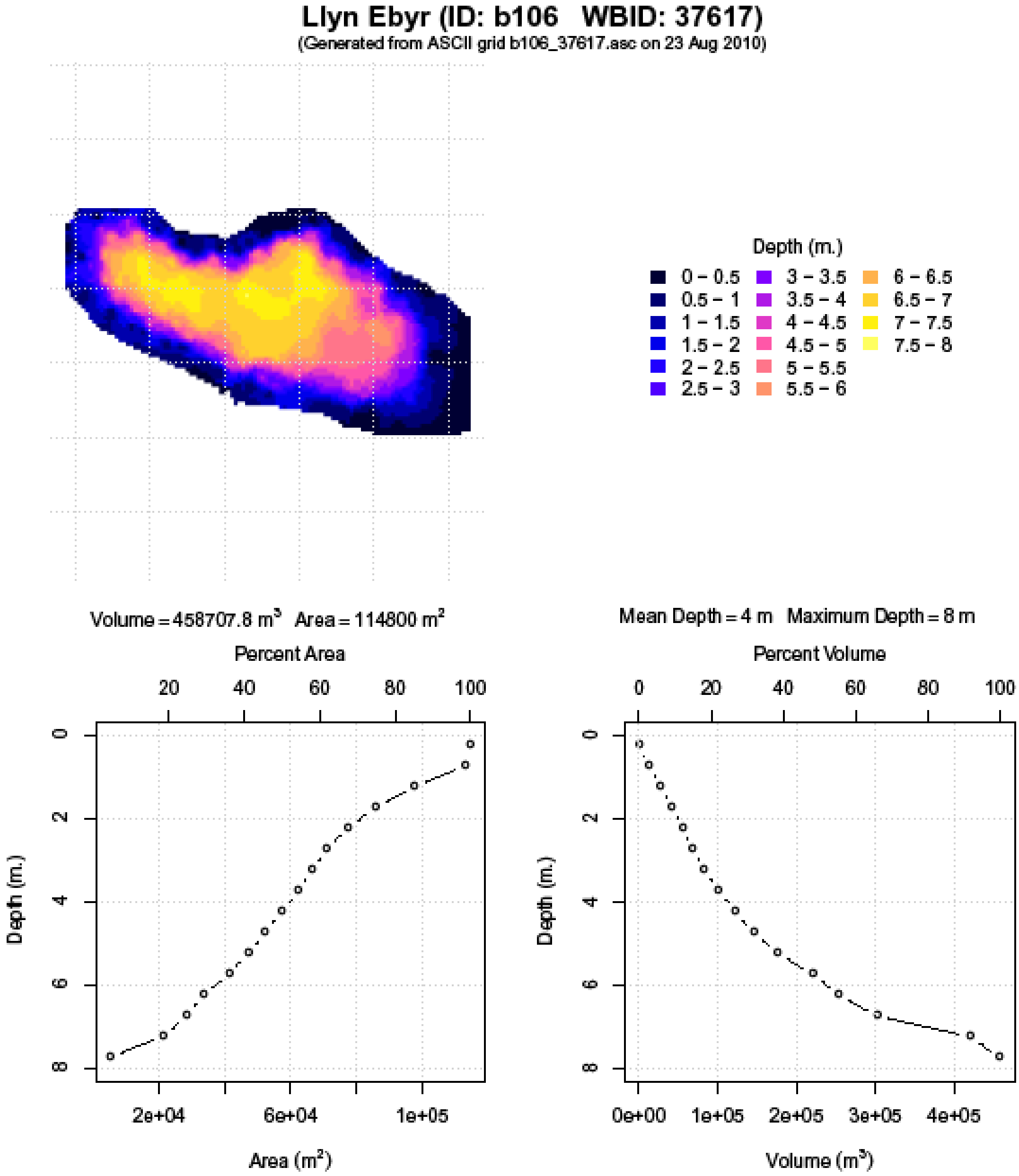


Figure A11.53 R: output compilation figure of Llyn Ebyr

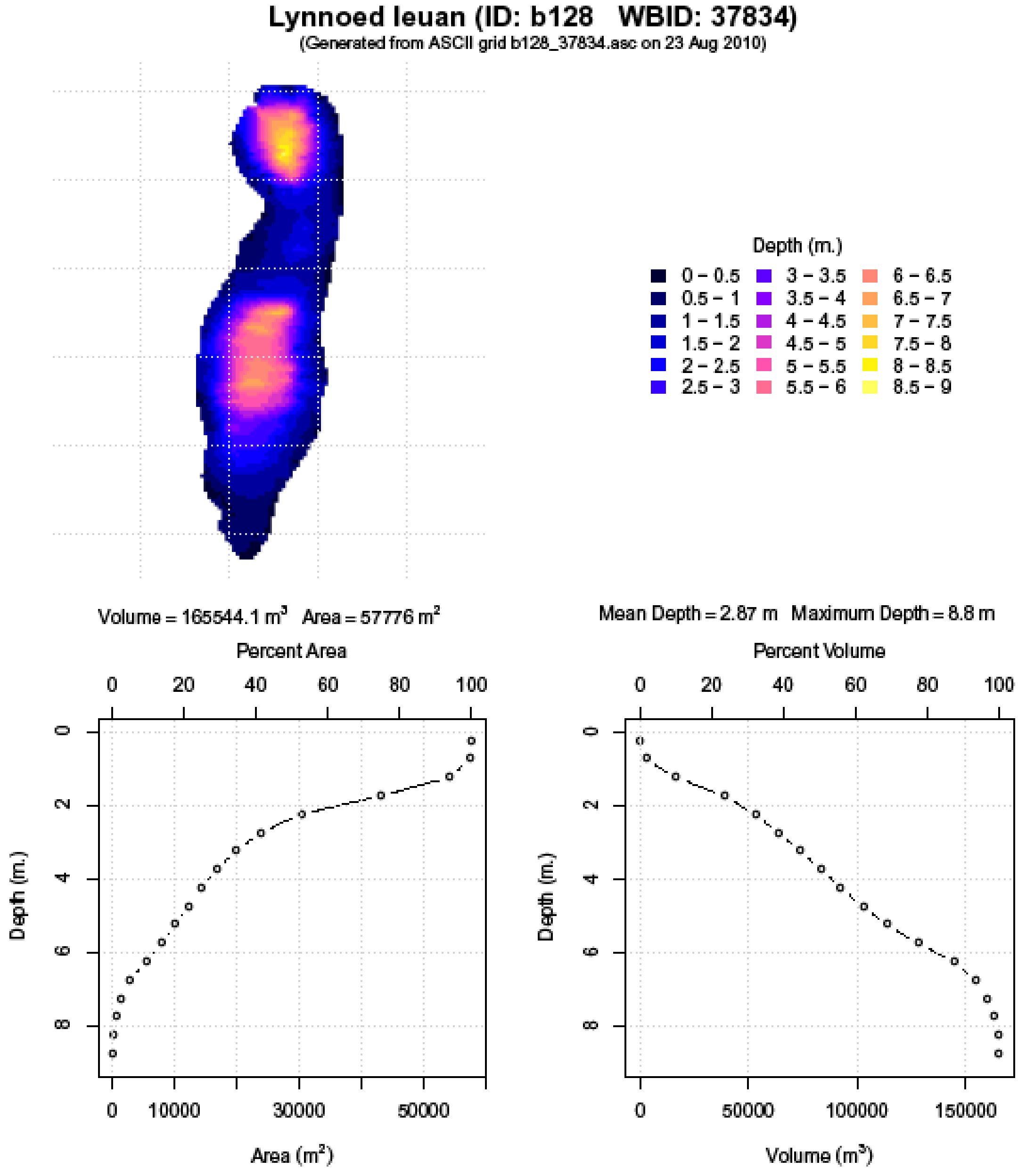


Figure A11.54 R: output compilation figure of Lynnoed Ieuan

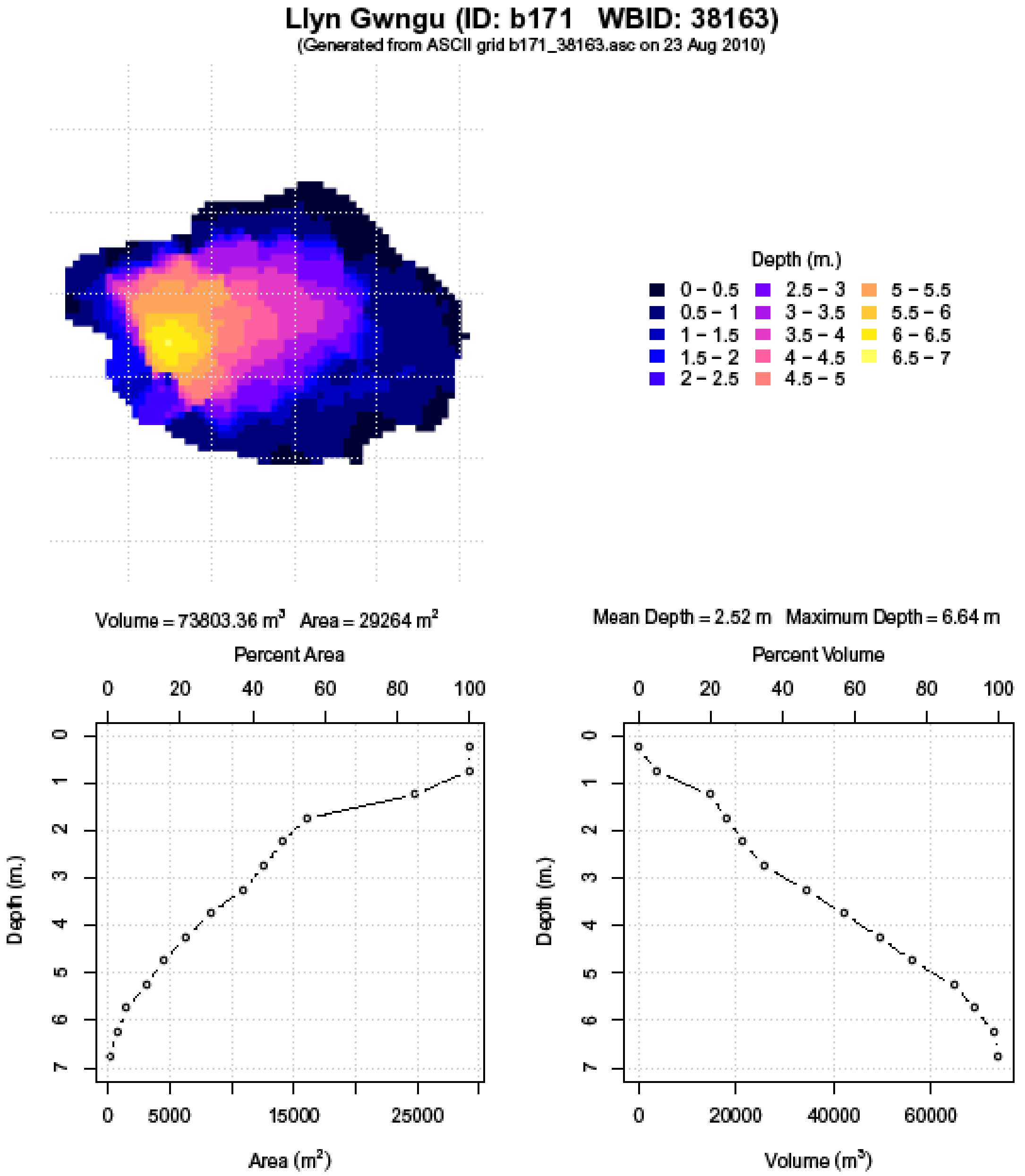


Figure A11.55 R: output compilation figure of Llyn Gwngu

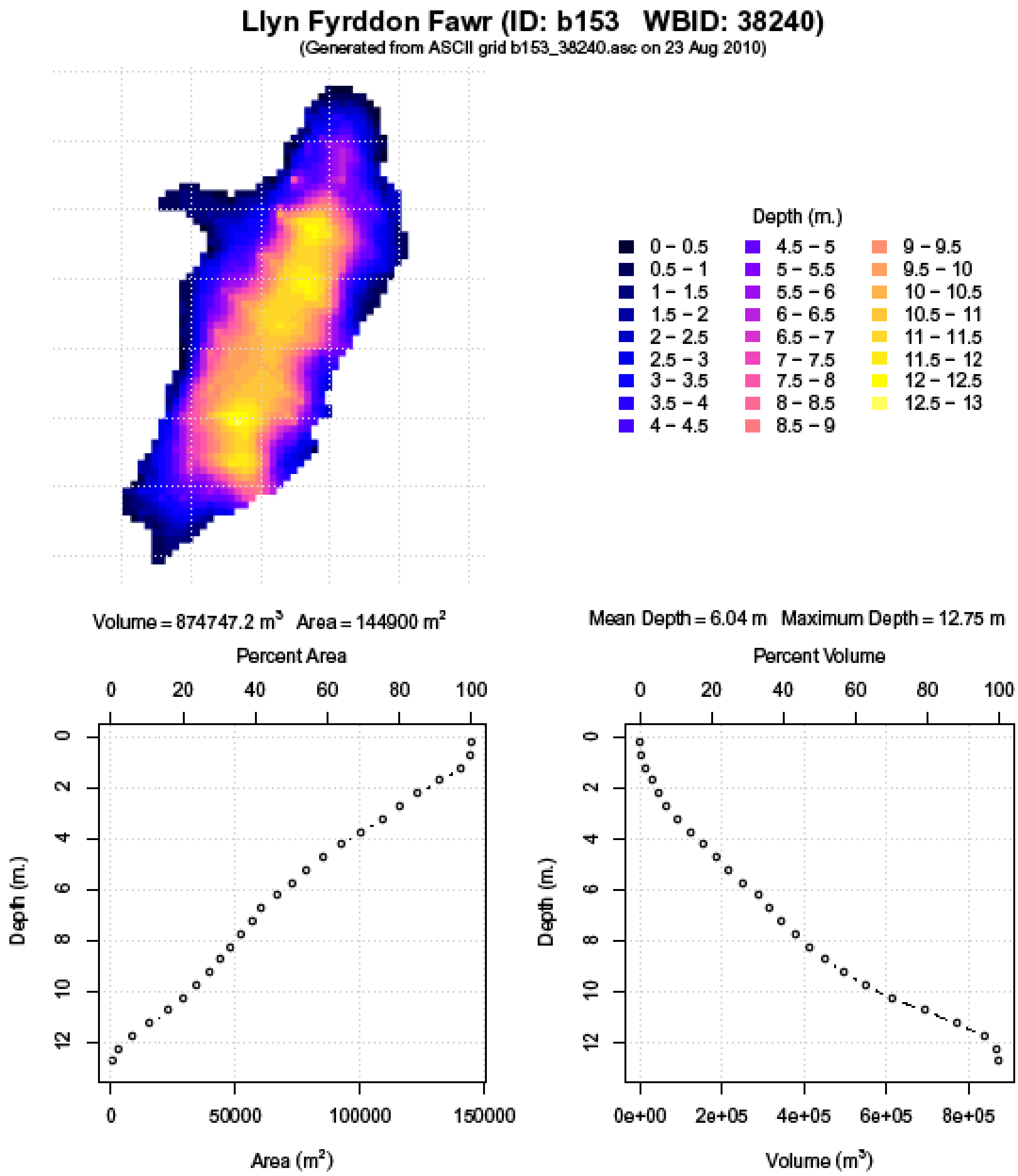


Figure A11.56 R: output compilation figure of Llyn Fyrddon Fawr

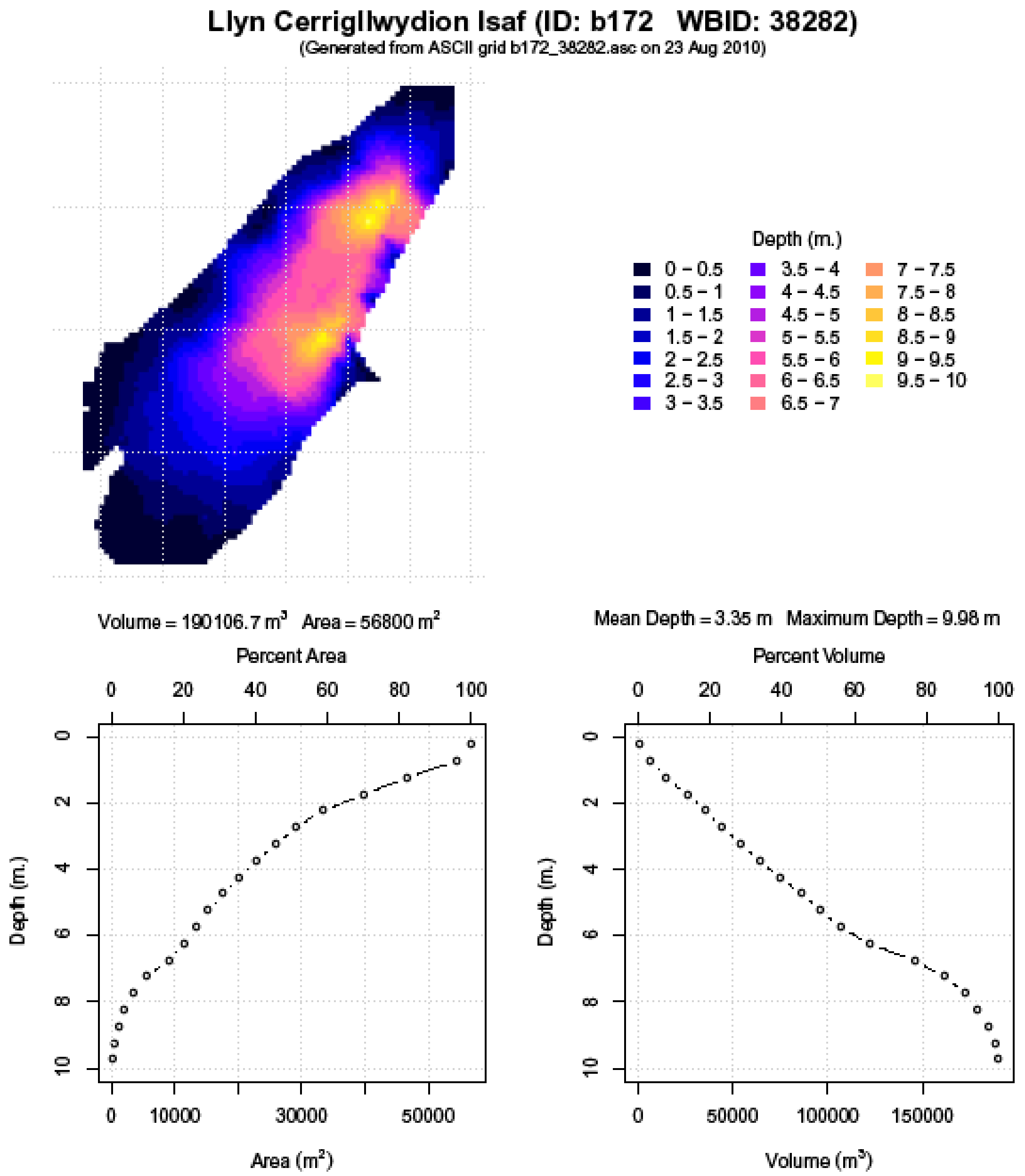


Figure A11.57 R: output compilation figure of Llyn Cerrigllwydion Isaf

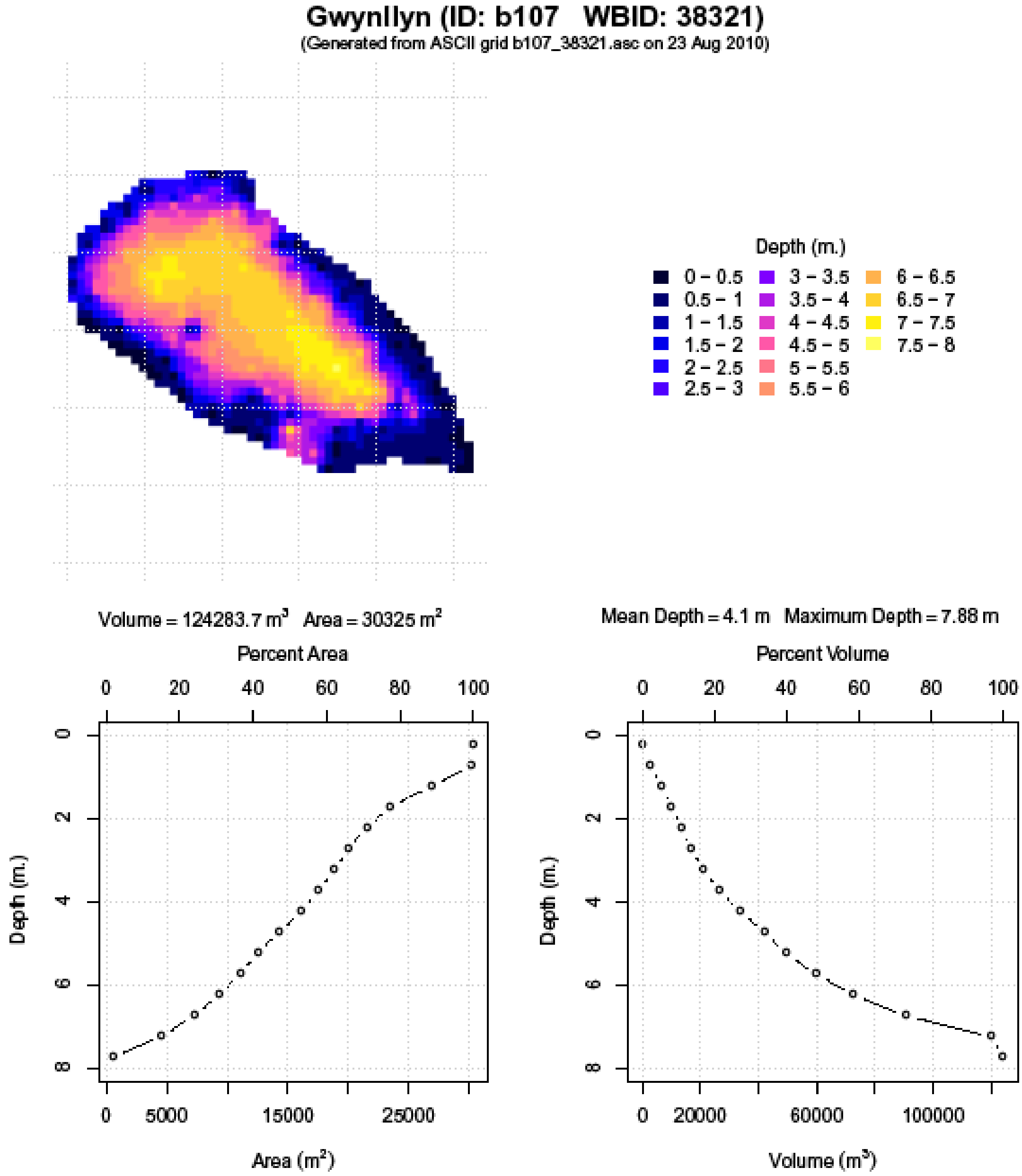


Figure A11.58 R: output compilation figure of Gwynllyn

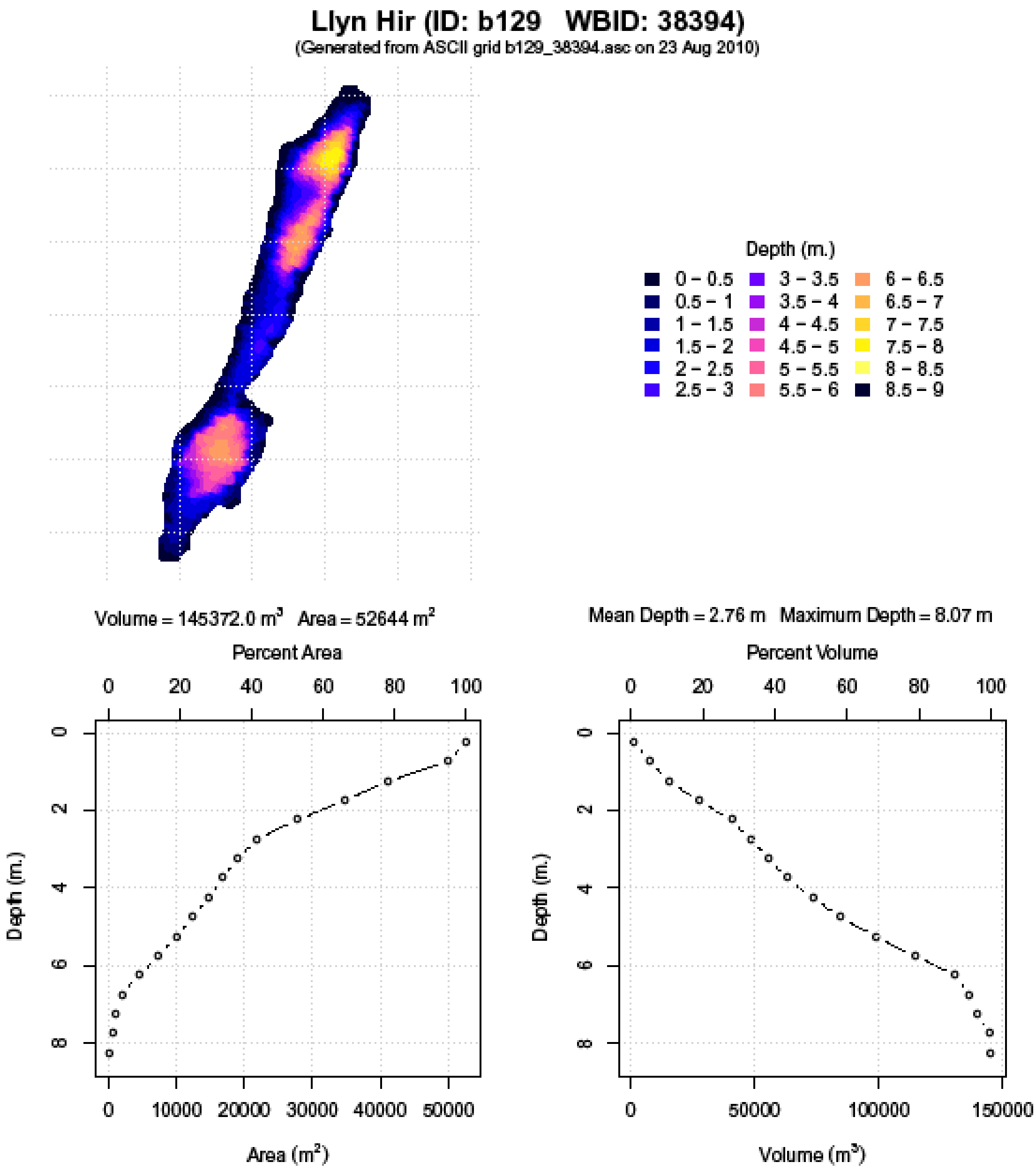


Figure A11.59 R: output compilation figure of Llyn Hir

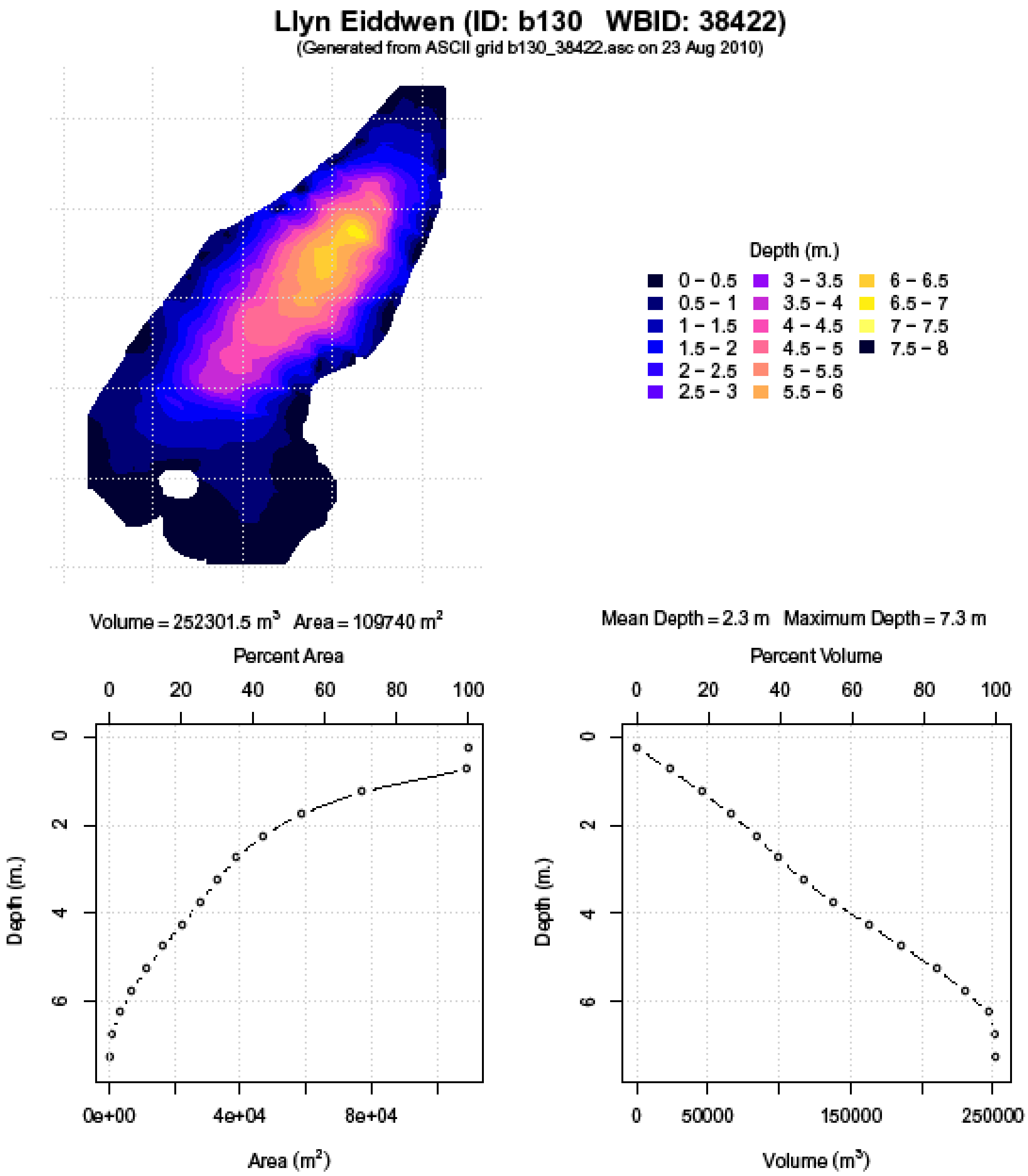


Figure A11.60 R: output compilation figure of Llyn Eiddwen

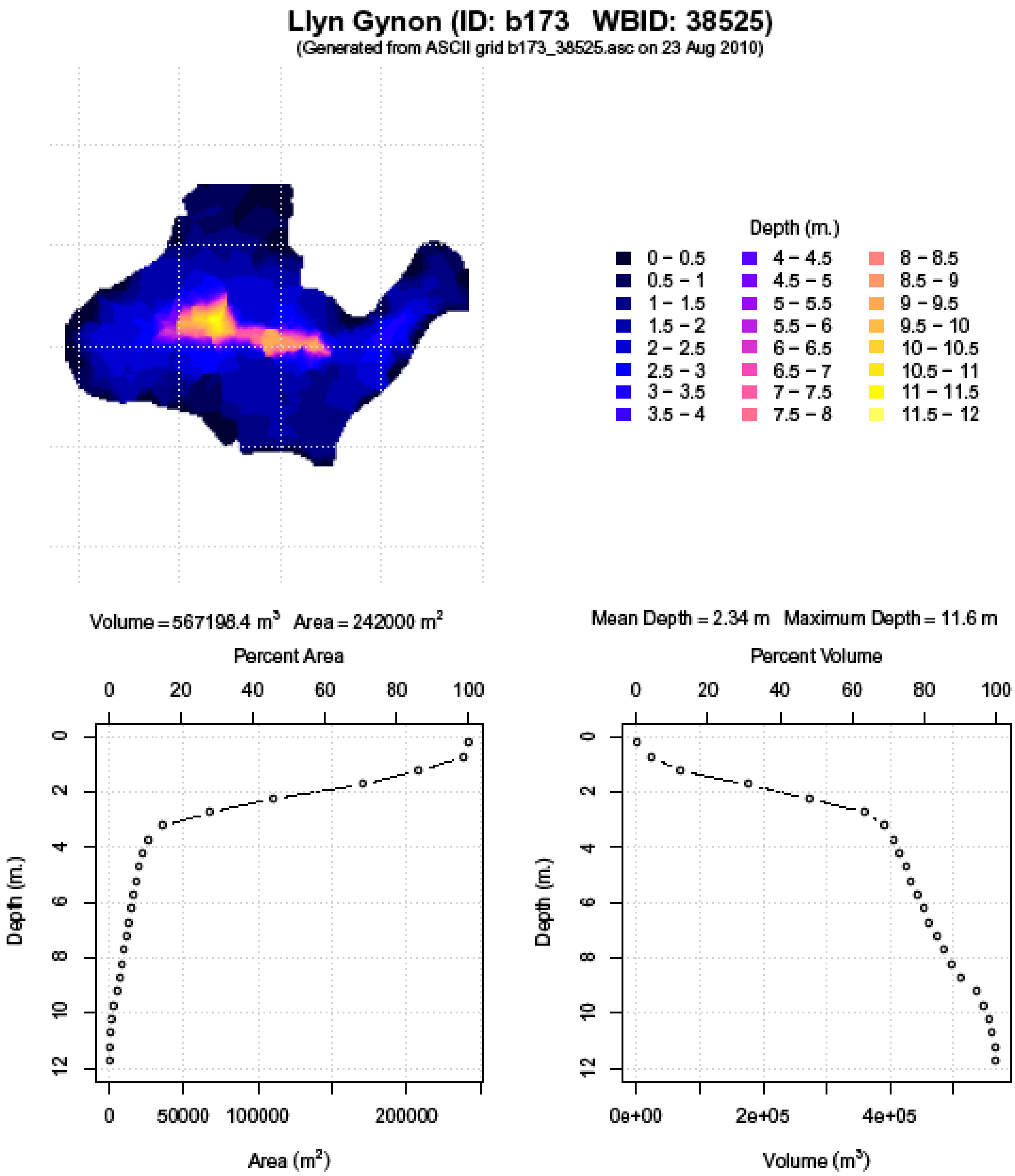


Figure A11.61 R: output compilation figure of Llyn Gynon

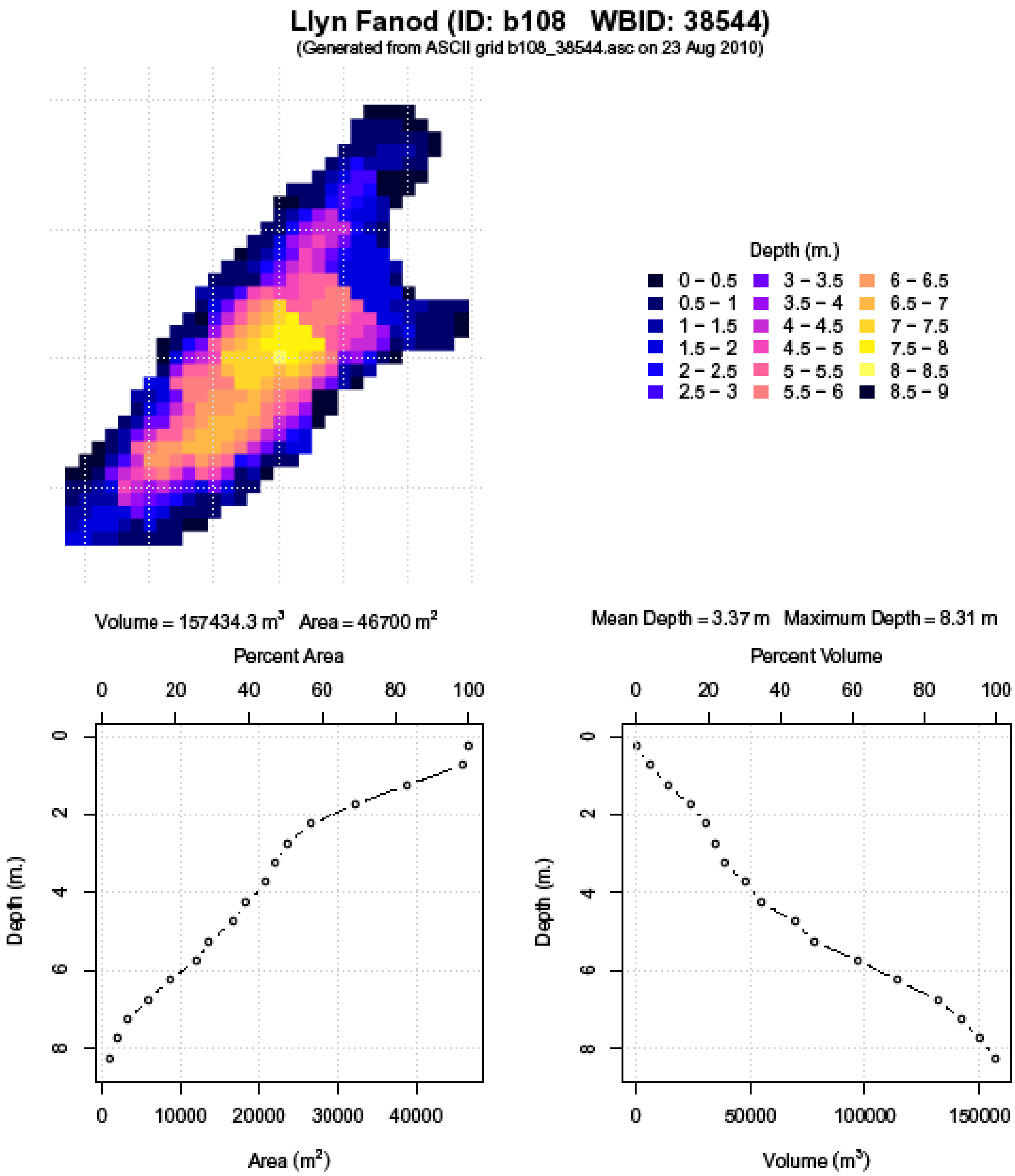


Figure A11.62 R: output compilation figure of Llyn Fanod

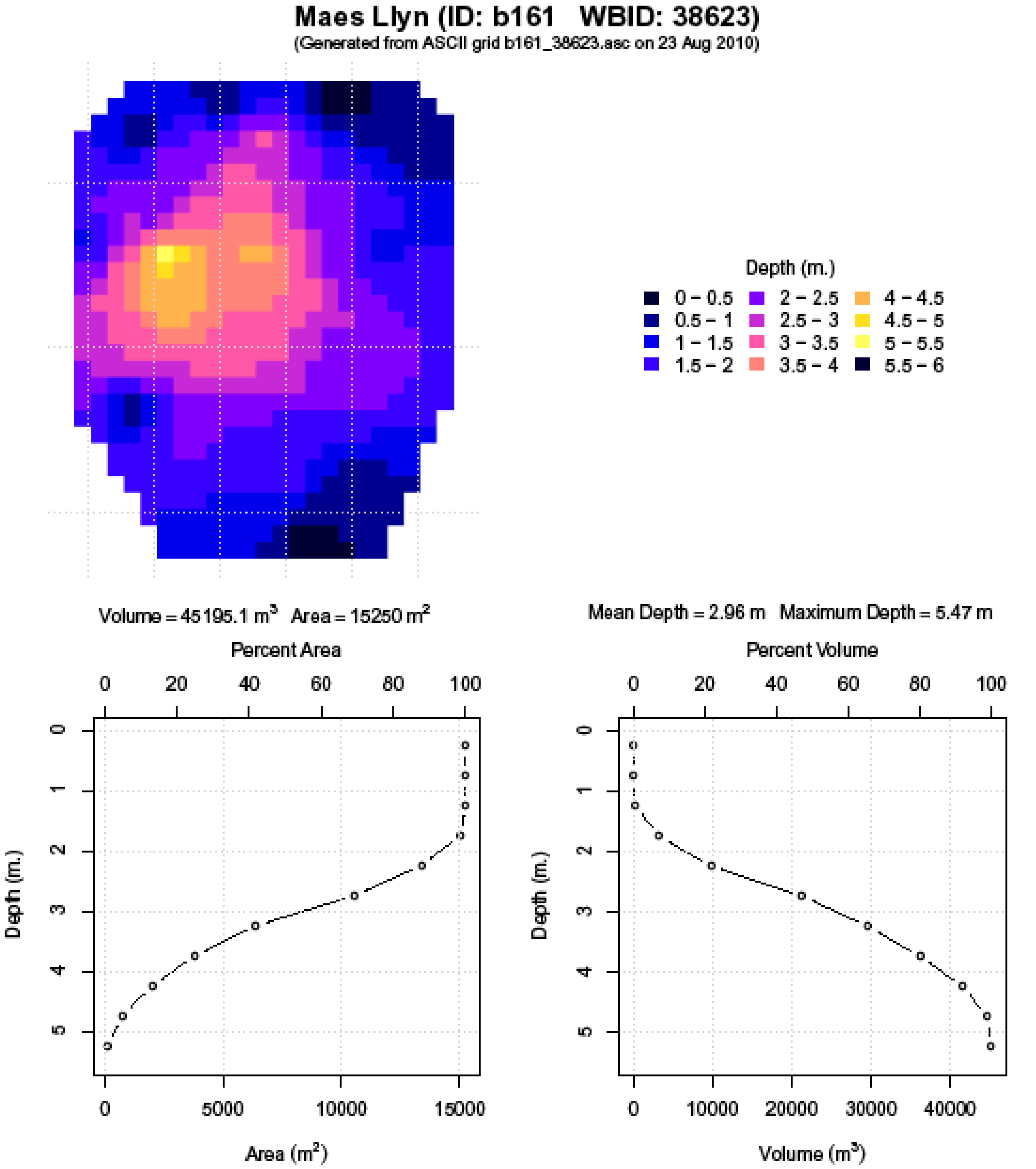


Figure A11.63 R: output compilation figure of Maes Llyn

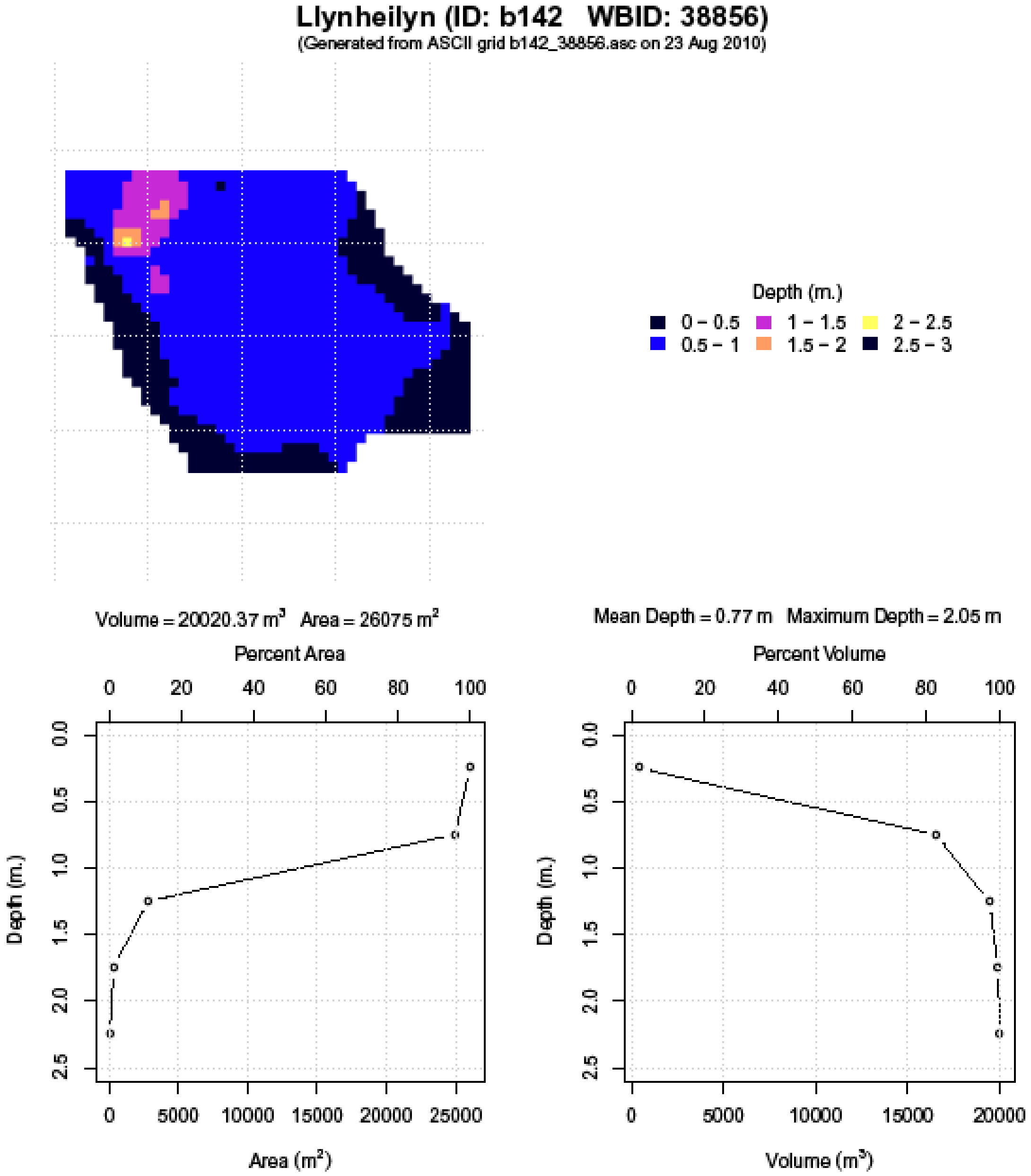


Figure A11.64 R: output compilation figure of Llynheilyn

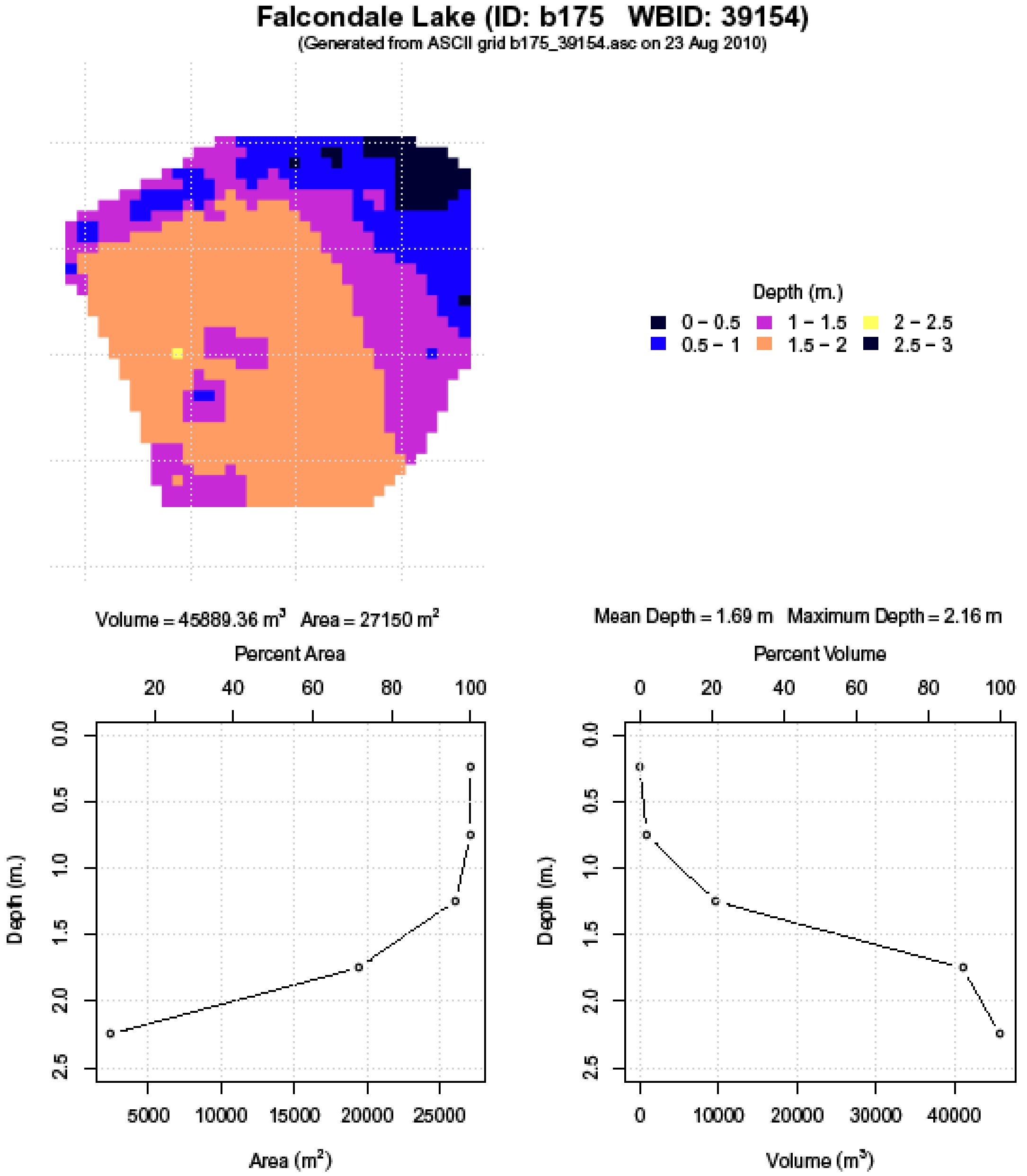


Figure A11.65 R: output compilation figure of Falcondale Lake

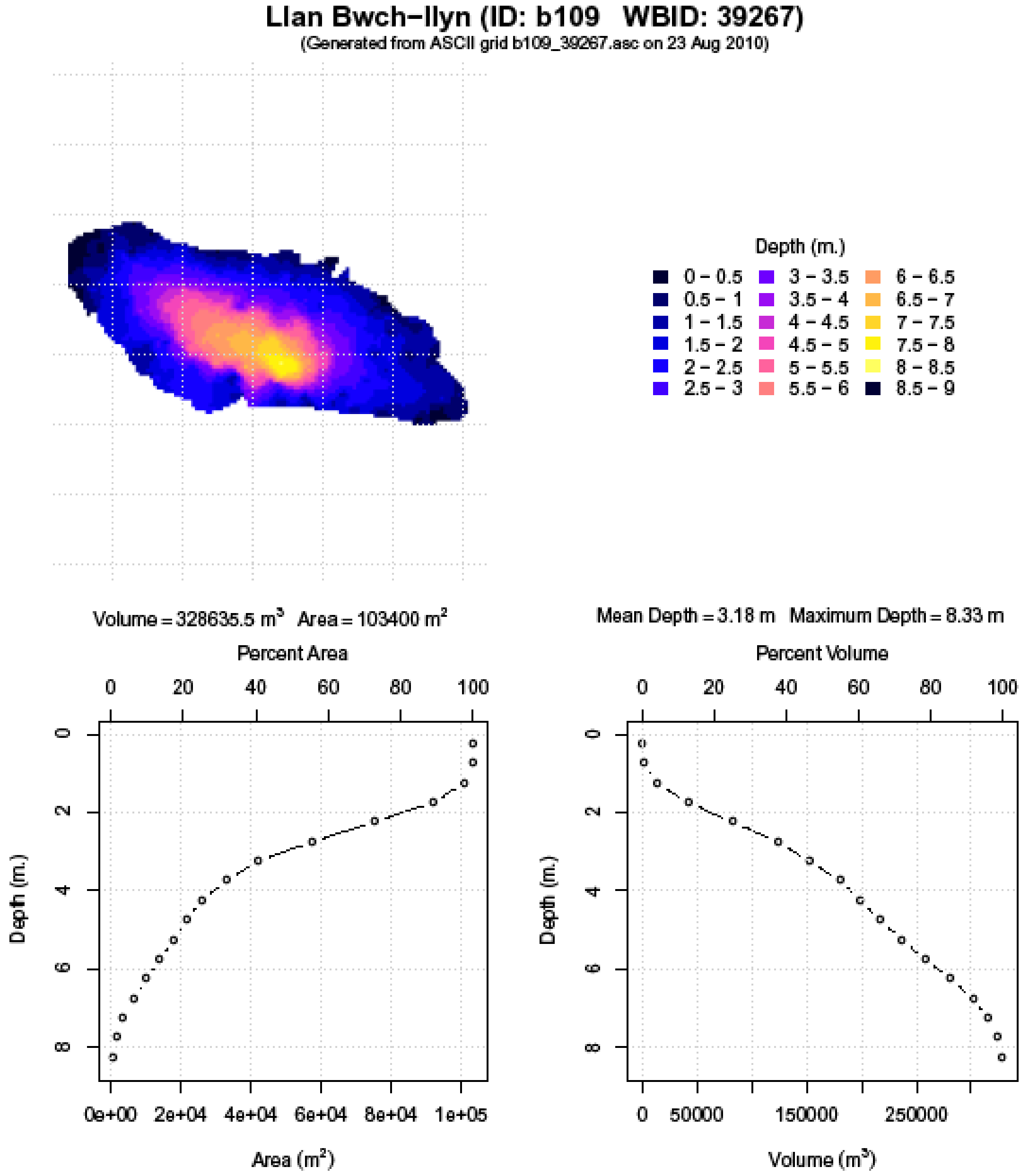


Figure A11.66 R: output compilation figure of Llyn Bwch-llyn

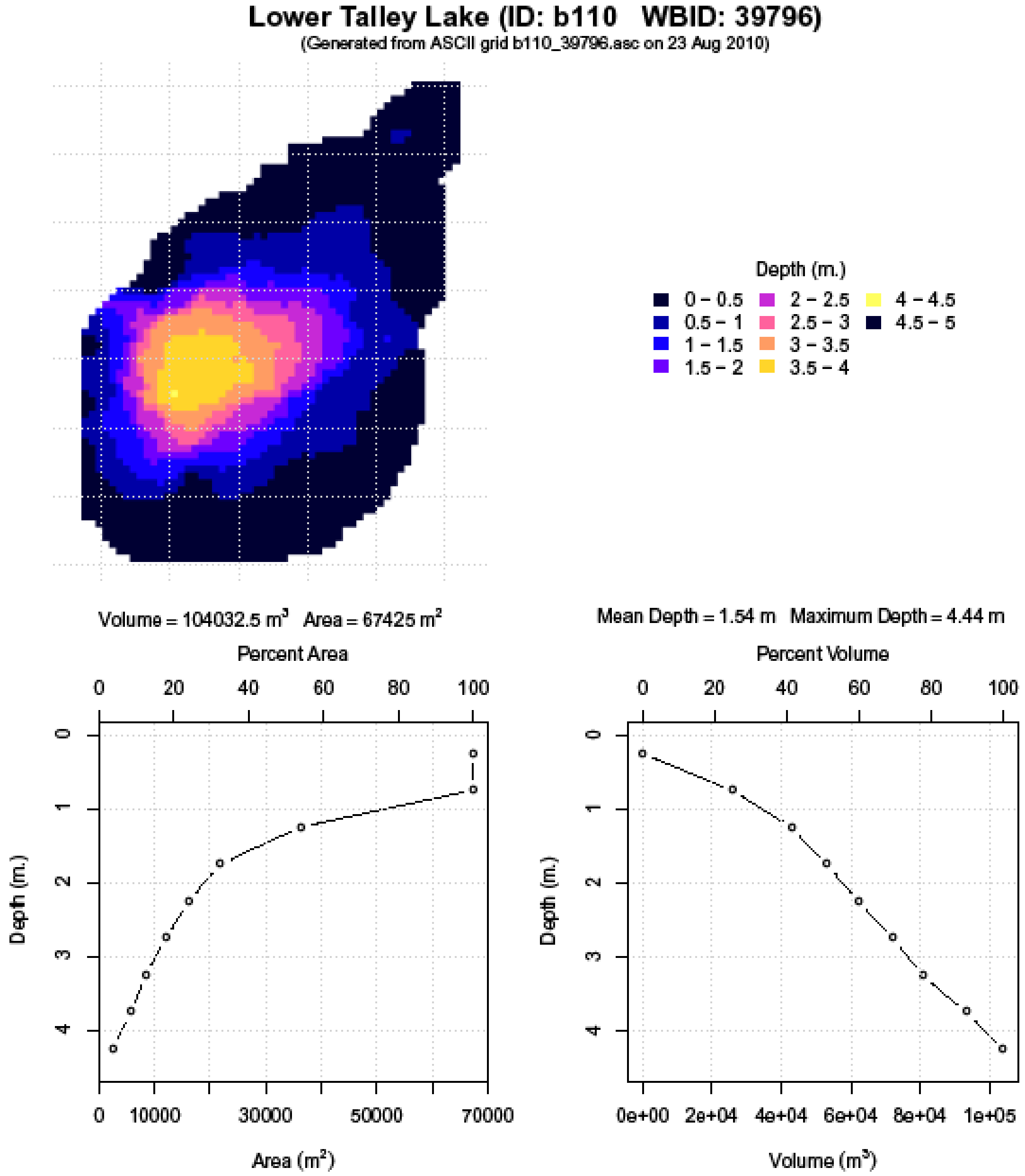


Figure A11.67 R: output compilation figure of Lower Talley Lake

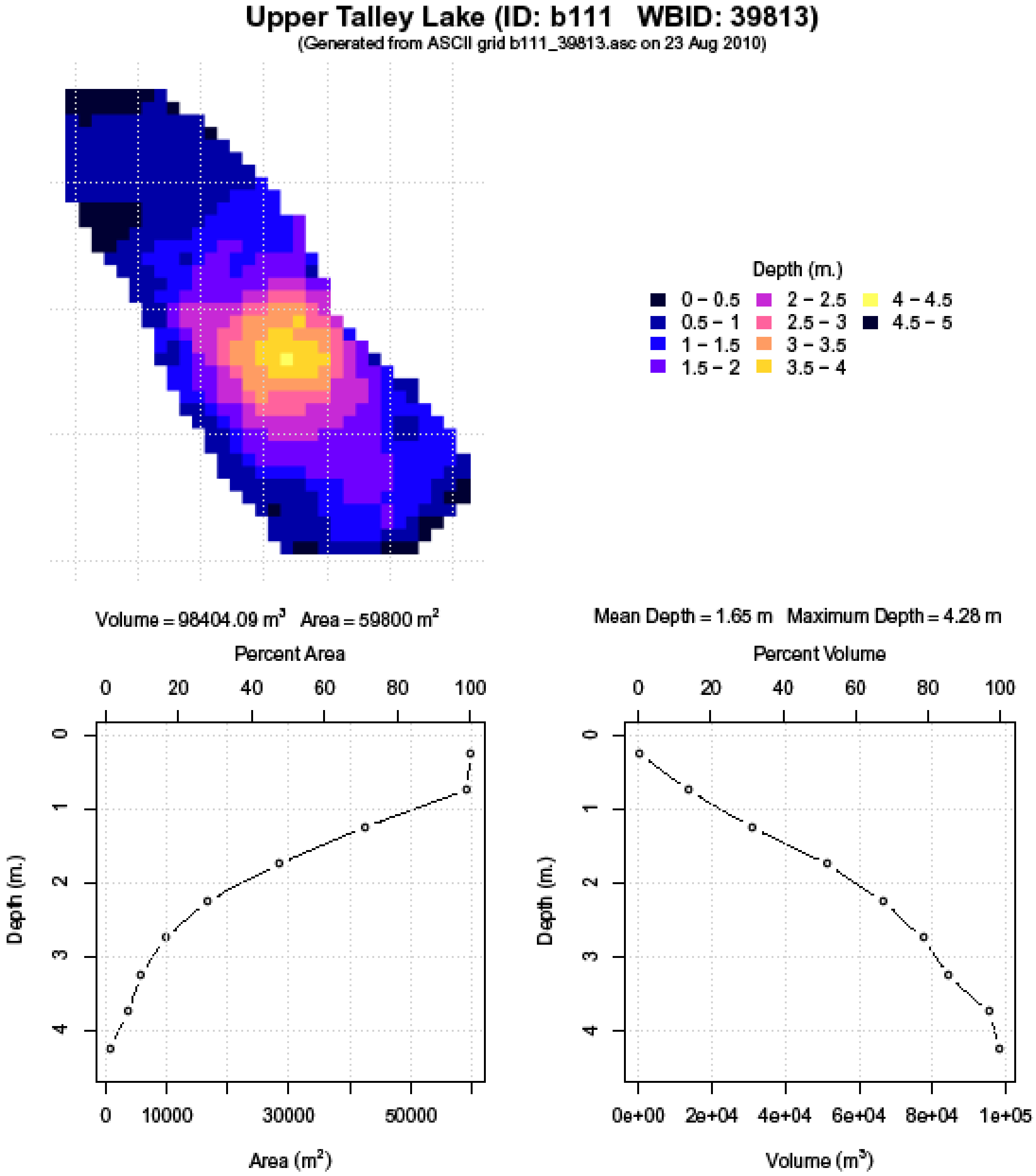


Figure A11.68 R: output compilation figure of Upper Talley Lake

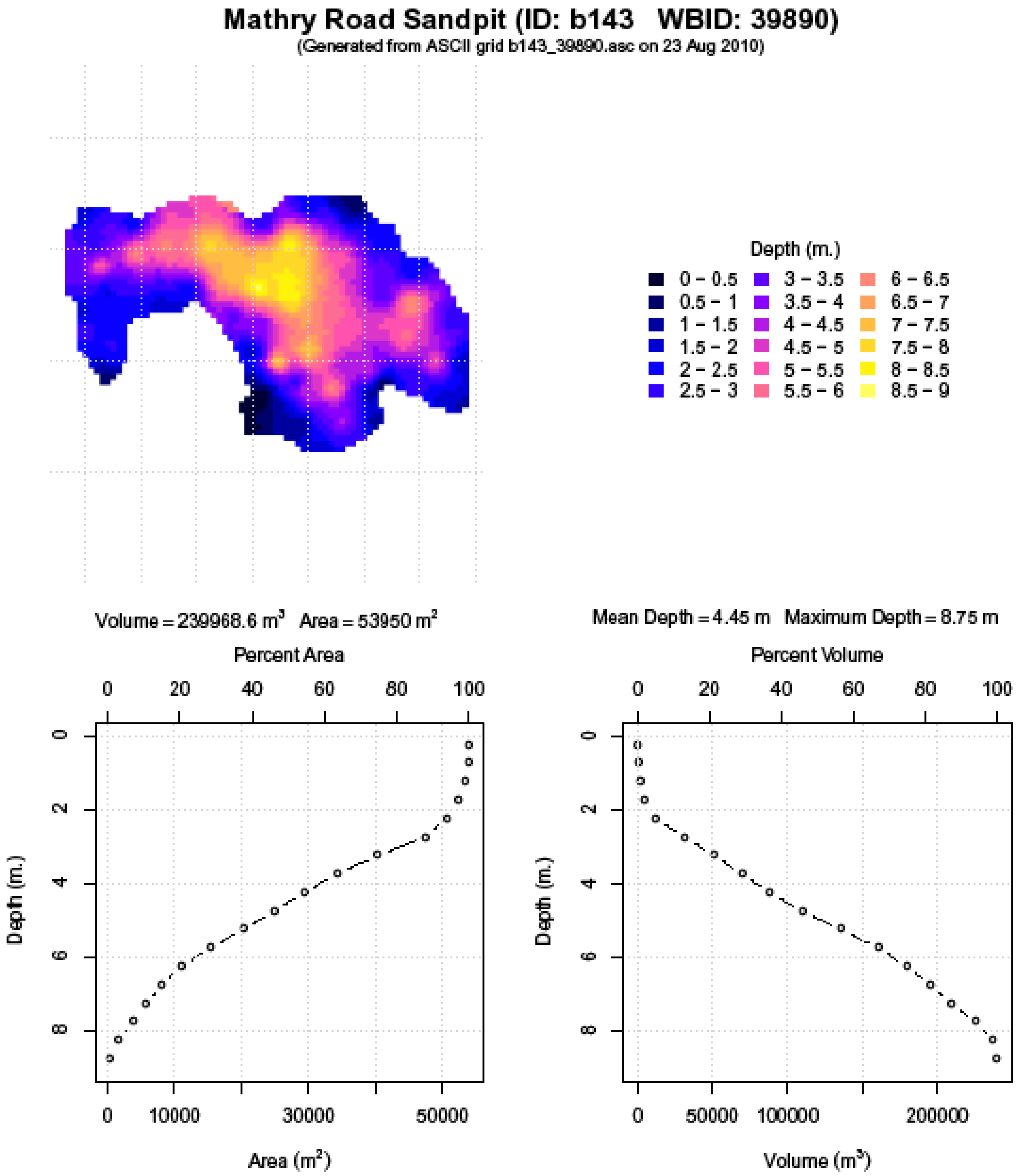


Figure A11.69 R: output compilation figure of Mathry Road Sandpit

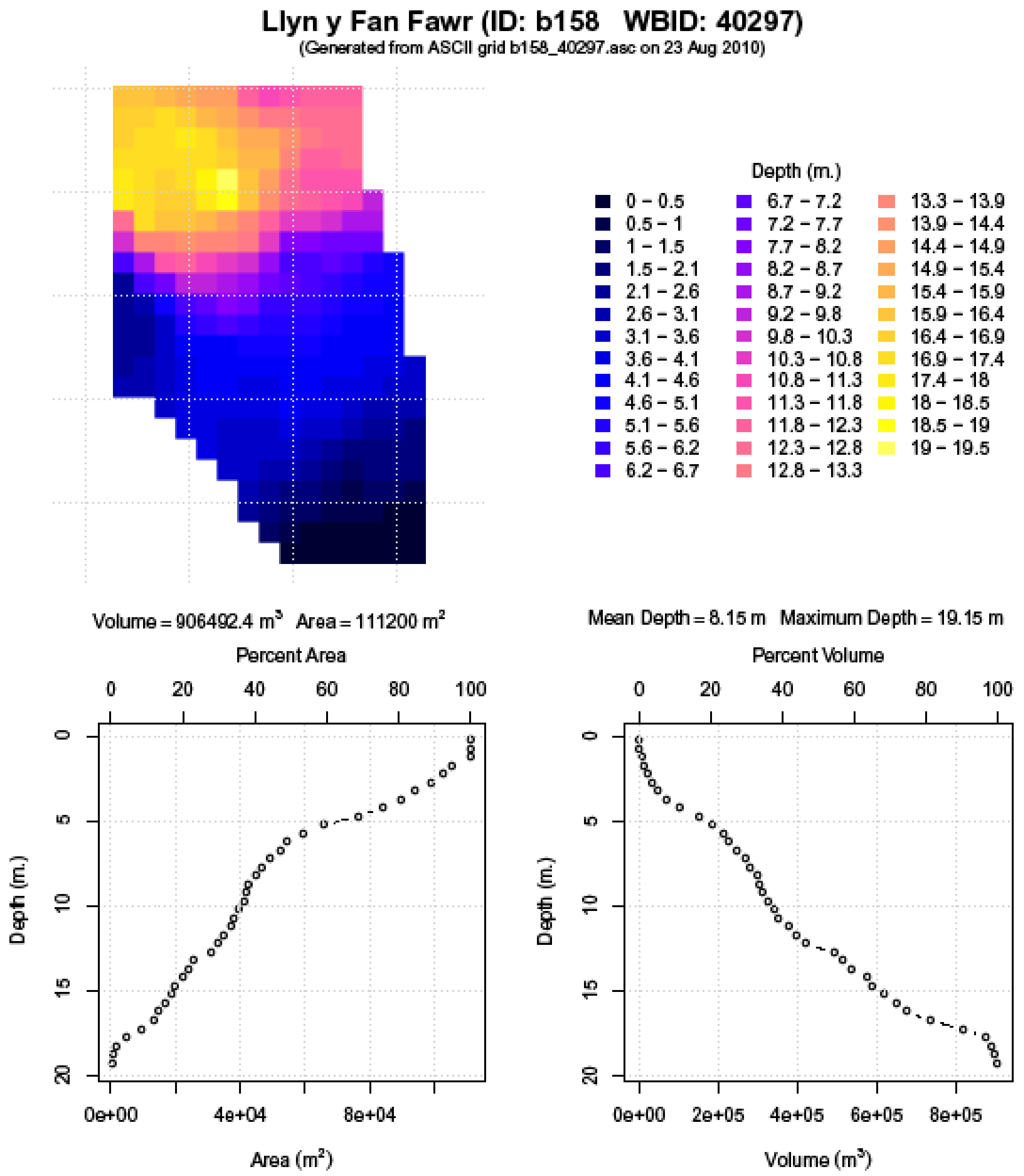


Figure A11.70 R: output compilation figure of Llyn y Fan Fawr

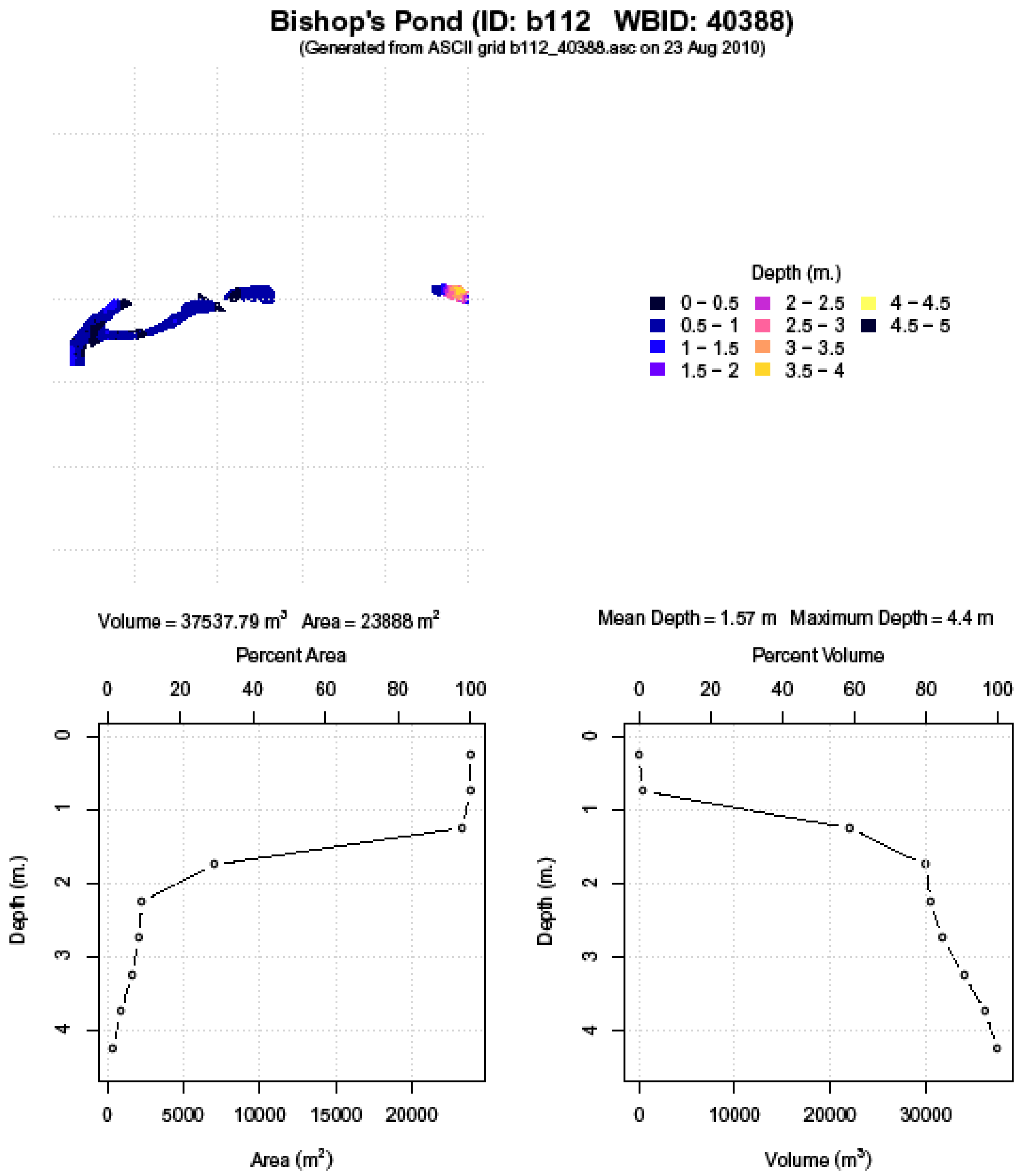


Figure A11.71 R: output compilation figure of Bishop's Pond

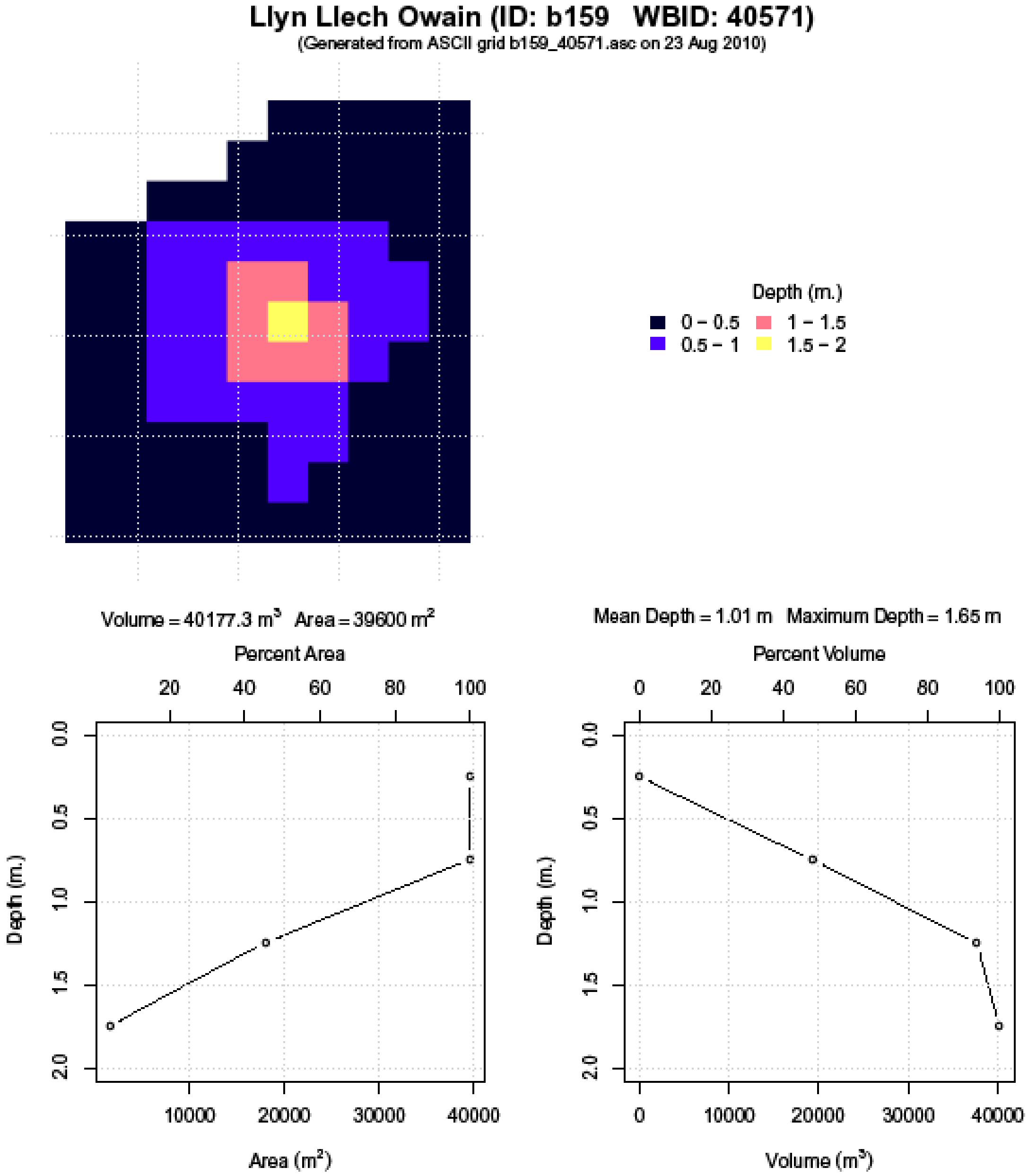


Figure A11.72 R: output compilation figure of Llyn Llech Owain

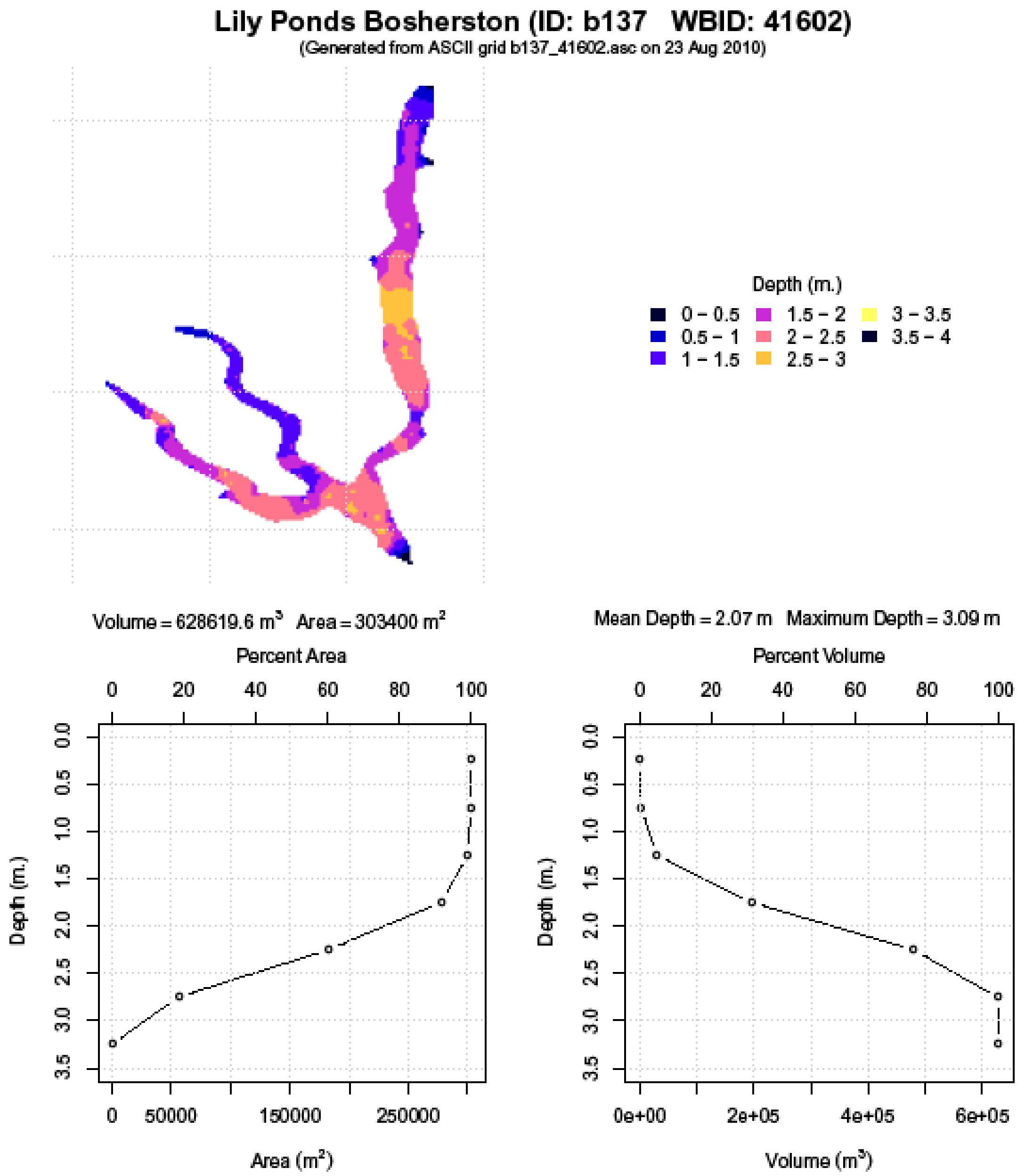


Figure A11.73 R: output compilation figure of Lily Ponds Bosherston

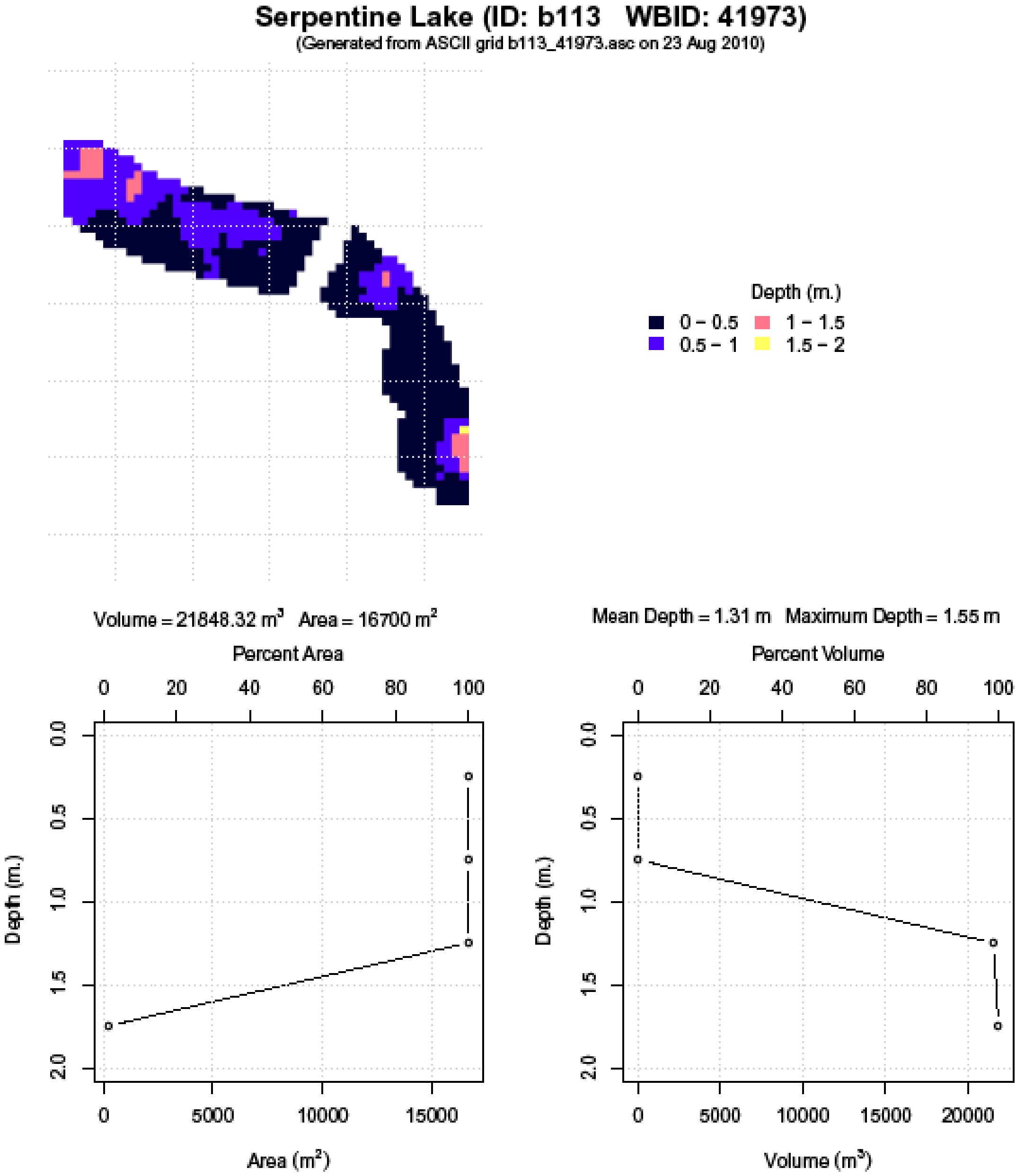


Figure A11.74 R: output compilation figure of Serpentine Lake

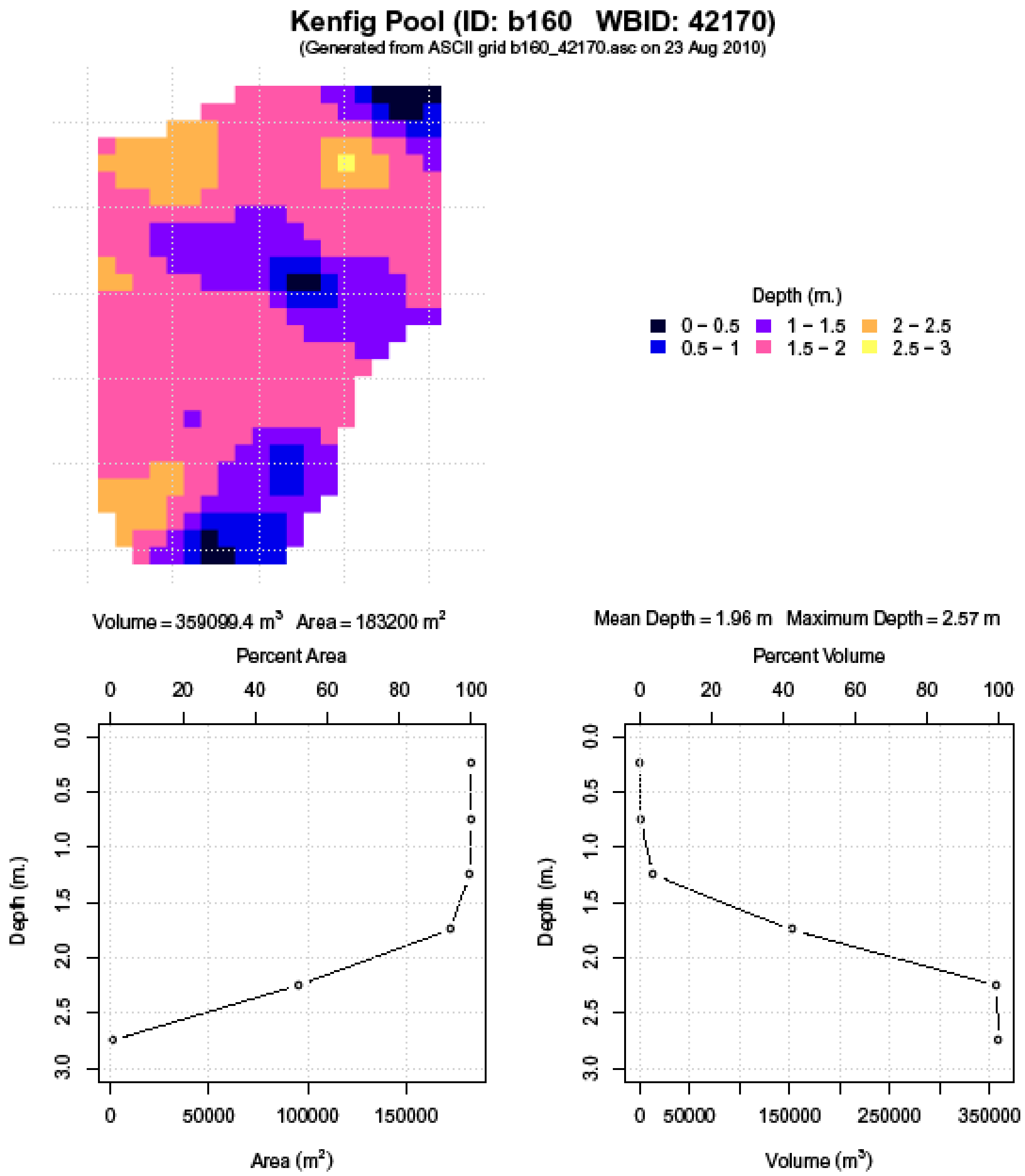


Figure A11.75 R: output compilation figure of Kenfig Pool

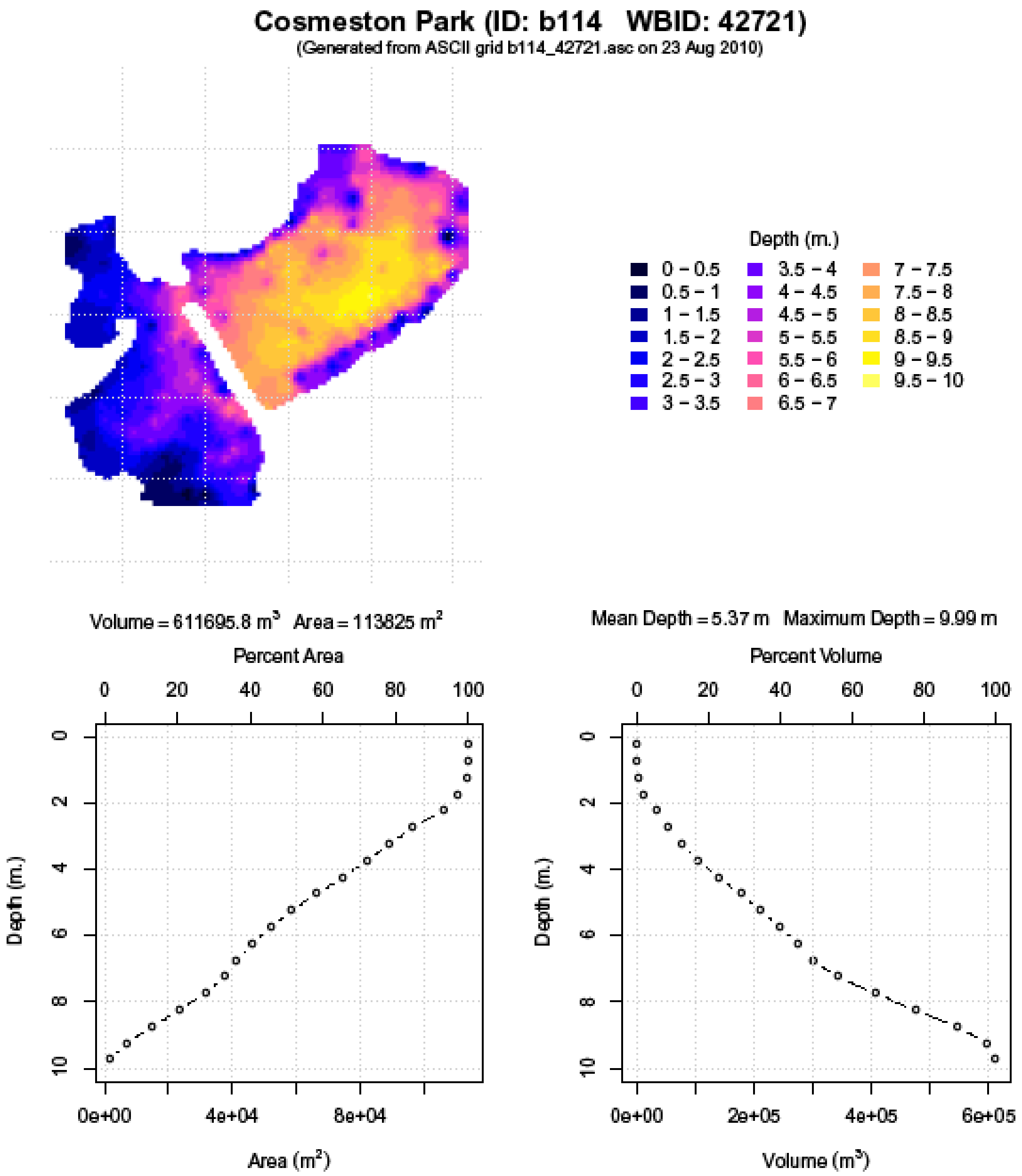


Figure A11.76 R: output compilation figure of Cosmeston Park

Appendix 12: Statistical version of bathymetry generation.

This R script can be found in the _docs folder

```
#######################################################################
##                                                                   ##
## Statistical Version of Bathymetry Generation                      ##
##                                                                   ##
## Gavin L. Simpson                                                  ##
##                                                                   ##
## 18 March 2011 (Version 1.0  )                                     ##
##                                                                   ##
## This work is licenced under a Creative Commons By Attribution 3.0 ##
## licence. Details of the licence are located here:                 ##
##                                                                   ##
## http://creativecommons.org/licenses/by/3.0/                       ##
##                                                                   ##
## Please cite as:                                                   ##
##                                                                   ##
## Simpson G.L. (unpublished R code)                                 ##
#######################################################################

## load required packages
require(mgcv)
require(soap)
## and for the spatial stack
require(rgdal)
require(sp)

## Load in a grid Llyn Anafon 2009 data plus outline
dataDIR <-
"/home/gavin/work/projects/ccw/data/CCW_Final_Data/33374_Llyn_Anafon_2009/."
outline <- readOGR(dataDIR, "33374_Llyn_Anafon_2009_lake_polyline")
depth <- readOGR(dataDIR, "d59_33374_xyz")

## Simple plot of the lake outline and the bathy data
plot(outline)
points(depth, pch = ".")

## coordinates of outline
crds <- coordinates(outline)[[1]][[1]]
outDf <- data.frame(Index = seq_len(nrow(crds)),
                    os_x = crds[,1], os_y = crds[,2],
                    x = crds[,1], y = crds[,2])
names(outDf) <- c("Index","os_x", "os_y", "x", "y")
outDf <- within(outDf, Depth <- 0)
coordinates(outDf) <- c("x", "y")
proj4string(outDf) <- proj4string(depth)
## merge depth and outDf
lakeData <- rbind(depth, outDf)

## grid for knots in soap film
coords <- coordinates(outline)[[1]][[1]] ## extract lake outline coords
## format these as a boundary object for soapfilm
bound <- list(list(x = coords[,1], y = coords[,2], f = rep(0, nrow(coords))))
## grid size along one dimension
N <- 8
## generate N points in x and y coords that cover the region/bounding box
gx <- seq(min(crds[,1]), max(crds[,1]), len = N)
gy <- seq(min(crds[,2]), max(crds[,2]), len = N)
## all combinations of gx gy
gp <- expand.grid(gx, gy)
names(gp) <- c("x","y") ## apply names to the grid of values
## this finds knots from the 8x8 grid that lie inside the lake
```

```
knots <- gp[inSide(bound, gp$x, gp$y), ]
## names the knots with the same names as the x and y coordinate variables
names(knots) <- c("os_x", "os_y")
names(bound[[1]]) <- c("os_x", "os_y", "f")

## generate a plot of the lake outline, the depth sounding locations
## the 8x8 grid of candidate knots, and finally the knots that are
## inside the lake outline
plot(outline)
points(depth, pch = ".")
points(gp)
points(knots, bg = "red", pch = 21)

## Soap film smoothers - fit the soapfilm
system.time(
m2 <- gam(-Depth ~ s(os_x, os_y, k = 10, bs = "so", xt = list(bnd = bound)),
          data = depth, method = "REML", knots = knots))

## generate some x and y limits for subsequent plots
lims <- apply(crds, 2, range)
ylim <- lims[,2]
xlim <- lims[,1]

## Produces a plot of the fitted soapfilm smoother and the lake
## outline, grid and chosen knots.
plot(m2, asp = 1, ylim = ylim, xlim = xlim, se = FALSE)
lines(outline, col = "red")
points(gp)
points(knots, bg = "red", pch = 21)

#######################################################################
## predictions - 5m grid
#######################################################################
##
## To produce a nice contour plot of the fitted bathymetry
## need a fine grid of points in the x and y coordinations
## this block of code does that creating a 5mx5m grid over
## the lake. Change `by = 5` to some larger number if 5x5m
## grid is too fine (e.g. for a large lake)
grid.x <- with(m2$var.summary,
               seq(min(c(os_x, crds[,1])), max(c(os_x, crds[,1])),
                   by = 5))
grid.y <- with(m2$var.summary,
               seq(min(c(os_y, crds[,2])), max(c(os_y, crds[,2])),
                   by = 5))
pdata <- with(m2$var.summary, expand.grid(os_x = grid.x, ox_y = grid.y))
names(pdata) <- c("os_x","os_y")

## This generates the predicted depth for each of our 5x5 grid cells
pred <- predict(m2, pdata, type = "response", se.fit = TRUE)

## depth interval breaks
interval <- 0.5 ## metres depth
dseq <- rev(-seq(0, max(slot(depth, "data")$Depth) + 0.5, by = interval))
cols <- rev(bpy.colors(length(dseq)-1))

## plot predicted bathymetry
plot(outline)
image(grid.x, grid.y, matrix(pred$fit, nrow = length(grid.x),
                             ncol = length(grid.y)),
      add = TRUE, col = cols, breaks = dseq)
points(depth, pch = ".")
lines(outline, col = "red", lwd = 2)
axis(side = 1)
```

```
axis(side = 2)
title(xlab = "os_x", ylab = "os_y", main = "Predicted Bathymetry")
box()
########################################################################
```