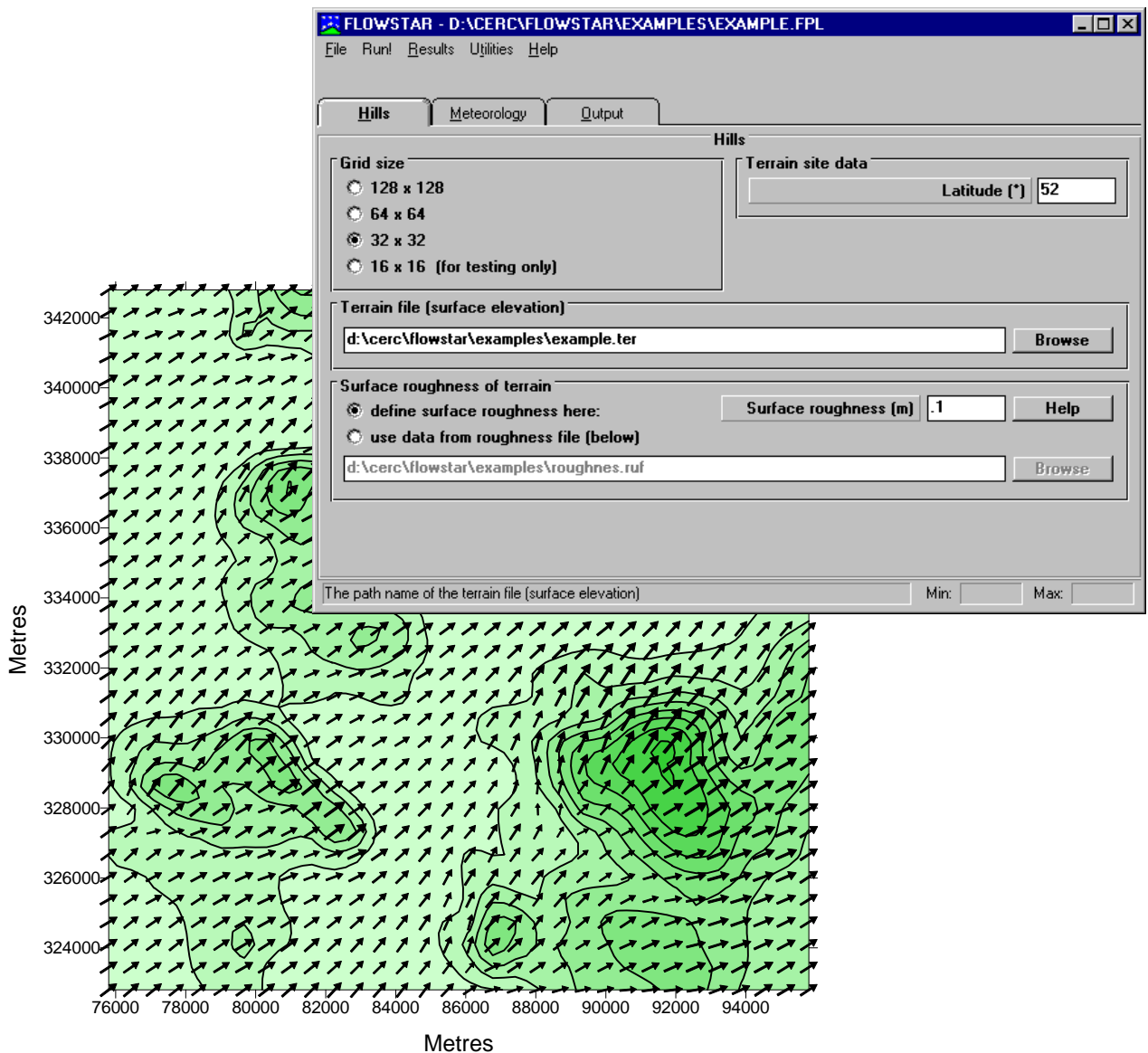




FLOWSTAR

*Modelling Flow Over
Complex Terrain*



User Guide

CERC

FLOWSTAR

User Guide

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SECTION ONE: INTRODUCTION

1.1 About FLOWSTAR

What is FLOWSTAR?

FLOWSTAR is a model developed by CERC to calculate air flow and turbulence over complex terrain, including the effects of stratification and variable surface roughness.

FLOWSTAR is supplied complete with a meteorological pre-processor and a utility for creating terrain data files for input to the model from OS Digital Terrain data for England, Scotland and Wales. A separate utility is required to convert OS digital data for Northern Ireland into terrain files. This is available from CERC. Detailed instructions can also be supplied on how to convert OS data for Eire into terrain files.

FLOWSTAR links to the contour plotting package Surfer for easy and effective display of results. More information about using Surfer with FLOWSTAR is provided in Section 4 and Appendix B.

What are the Main Applications of FLOWSTAR?

Applications of the model include:

- (i) Predictions of the wind field for wind farm planning.
- (ii) Wind engineering – for example flow in the proximity of a proposed bridge or flyover.
- (iii) Forestry – assessing where forests are most exposed to destructive winds.
- (iv) Pollution dispersion – FLOWSTAR is used in ADMS, CERC's air dispersion model, for calculating plume trajectory and spread in complex terrain.

Model Theory

FLOWSTAR is derived from the theoretical work of Jackson and Hunt (1975), and Hunt et al (1988a, 1988b). The model is based on the premise that different processes dominate the flow dynamics in layers at different heights above the ground; thus in the inner layer shear stress perturbations are locally important and are described by a mixing length closure whilst the flow is also impacted upon by pressure gradients. These can be determined from the outer layer flow where stratification plays an important role but

where shear stress perturbations have little influence. There is a transitional or middle layer between the inner and outer layer.

The description of the atmospheric boundary layer in FLOWSTAR is that of ‘new generation’ models, i.e. the atmospheric boundary layer is described not in terms of the single parameter Pasquill Class but in terms of two parameters, namely the boundary layer height, h , and the Monin-Obukhov length, L_{MO} .

Validation of the model (e.g. Carruthers et al, 1982) shows that FLOWSTAR models the flow well typically for slopes up to 1 in 2 (upwind slopes and hill summits) and up to 1 in 3 locally in hill wakes. The model is also valid for larger slopes, though it may locally underestimate flow perturbations. Spatial scales treated by the model range from tens of metres up to several kilometres.

1.2 About this User Guide

This FLOWSTAR *User Guide* is both a manual and a technical summary.

SECTION 1 INTRODUCTION

Introduces FLOWSTAR.

SECTION 2 GETTING STARTED

Provides information about model installation, system requirements and getting around the FLOWSTAR interface.

SECTION 3 INPUT

Describes the three screens of the FLOWSTAR interface (Hills, Meteorology and Output).

SECTION 4 OUTPUT

Describes FLOWSTAR results and describes the ways in which results can be displayed.

SECTION 5 TECHNICAL SUMMARY

Summarises the technical details of the FLOWSTAR model.

REFERENCES

Lists details of documents referred to in the User Guide.

APPENDICES

APPENDIX A Choosing Meteorological Data

Describes the different ways of inputting met. data into FLOWSTAR, how to obtain met. data and the applicability of each type of data in modelling.

APPENDIX B Viewing Terrain Data and Creating Files from OS Digital Data

Describes the format of OS terrain data required to use FLOWSTAR in the UK, how to obtain them and convert them to FLOWSTAR input format.

APPENDIX C Sources of Help and Contact Information

Lists contacts at CERC and details of the maintenance contract together with other contact information for met. data, map data, etc.

1.2.1 Conventions

To make this User Guide simpler to use, certain conventions have been followed with regard to layout and style.

- FLOWSTAR interface controls are shown in Arial font, e.g. the Grids screen, click on the Plot button.
- Keyboard keys are shown in bold, e.g. press **Enter**.
- Directory and file names are shown in italics, e.g. *flowwin.exe*, *<install_path>\data*.
- Tips and other notes are shown thus:

Think about the area you want to include in the calculation before specifying the terrain data.

- Table and figure references are shown in bold, e.g. see **Table 3.2**, **Figure 2.1**.

SECTION TWO: GETTING STARTED

2.1 System requirements

FLOWSTAR is a 32-bit program that is supported for use on PC's with Windows XP Professional environment. It is *recommended* that FLOWSTAR is installed on a computer with at least 128 MB of RAM and 1 GB of hard disk space. The model will run, although more slowly, on some machines of lower specification.

2.2 Installation

The installation of FLOWSTAR uses an Installation Wizard, which guides the user through a short series of screens, collecting information on the user and installation parameters, before installing the software.

Please check first with your own IT personnel for company procedures for installing software.

Step 1 You should log on as local administrator for the PC.

Step 2 To begin the FLOWSTAR install procedure, insert the FLOWSTAR CD. The install procedure should start automatically. If it does not, click on the Windows Start button, select Settings and then Control Panel. Double-click on the Add/Remove Programs icon and press the Install... button. Browse for the CD-ROM drive and select *setup.exe* in the root directory on the drive.

In both cases, the screen shown in **Figure 2.1** will be launched.

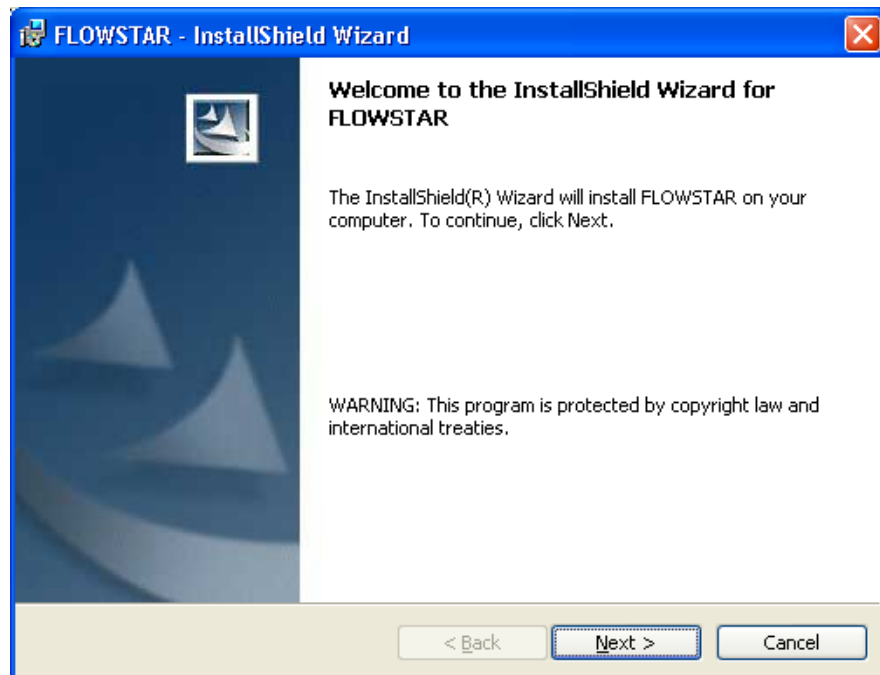


Figure 2.1 - The FLOWSTAR Installation Welcome screen.

Step 3 Click Next> through the Welcome and Licence Agreement screens (if appropriate) to get to the Customer Information screen, as shown in Figure 2.2.

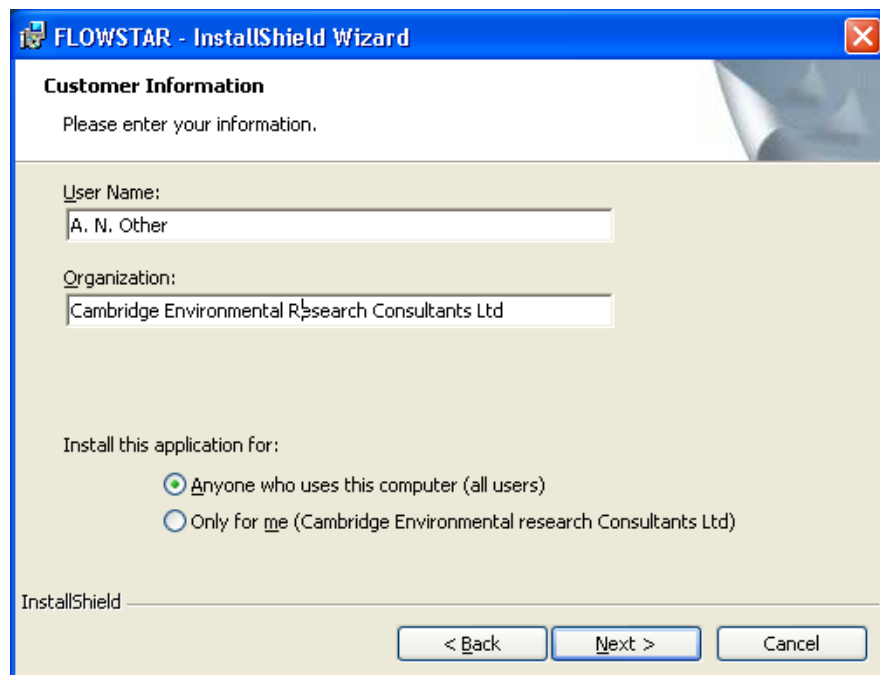


Figure 2.2 - The FLOWSTAR Customer Information screen.

Step 4 Enter your user name and organization in the designated places. You have the option of installing FLOWSTAR for all users or just for you. If you select **Only for me**, the model will only be available to the user logged in for this install. Click **Next>** to go through to the Destination Folder screen, as shown in **Figure 2.3**.

Step 5 You should select a drive with at least 1GB of available disk space. The default installation directory is *C:\Program Files\CERC\FLOWSTAR* but we suggest you install it in *<Drive>\CERC\FLOWSTAR*, where *<Drive>* can be *C:* or another drive of your choice. Use the **Change...** button to select your own installation directory (**Figure 2.4**). Click **OK** to return to the Destination Folder screen.

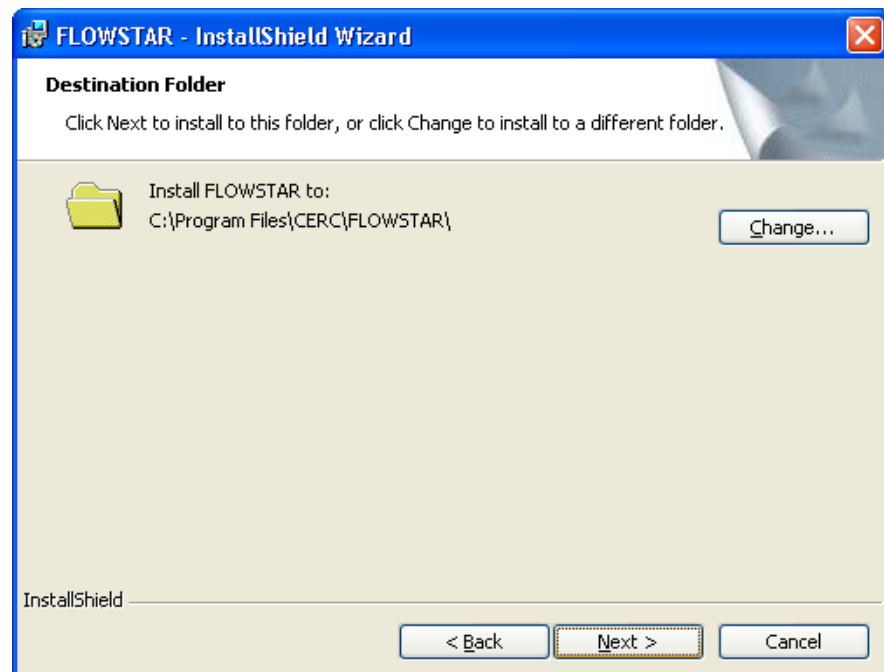


Figure 2.3 - The FLOWSTAR Destination Folder screen.

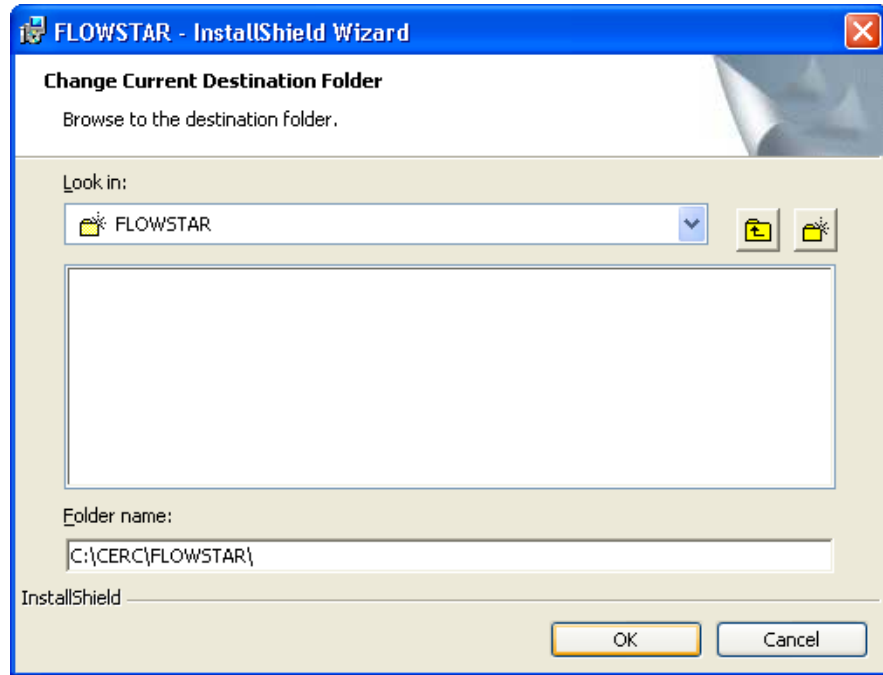


Figure 2.4 - The Change Current Destination Folder screen.

The abbreviation <install_path> will be used in the rest of the User Guide to denote the installation directory you have chosen, e.g. c:\cerc\FLOWSTAR.

Click Next> to view the options you have specified, as shown in **Figure 2.5**.

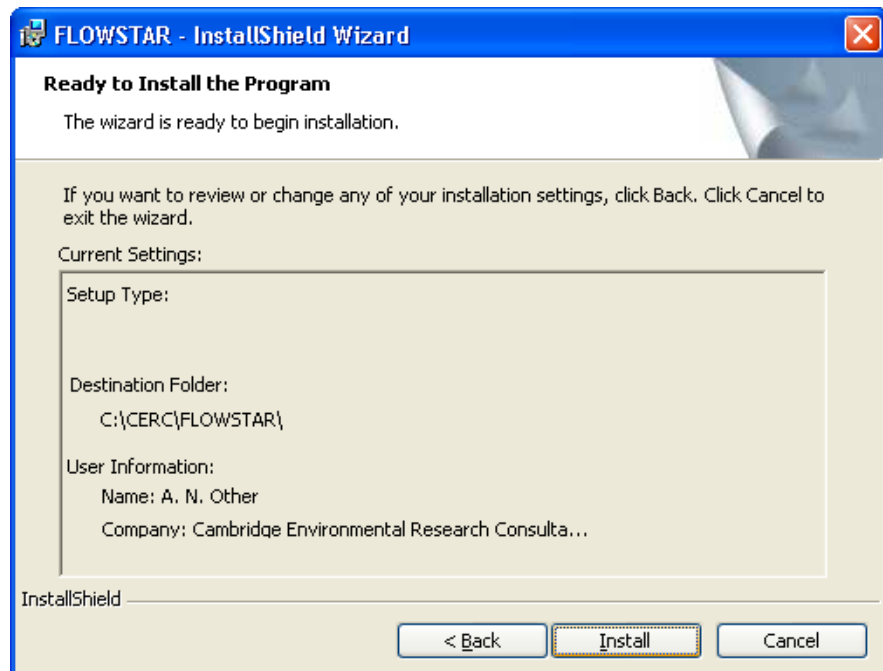


Figure 2.5 - The FLOWSTAR Install Current Settings screen.

Step 6 If the settings shown are correct, press the Install button to complete the install procedure. However, if you first wish to amend any details, press the <Back and Next> buttons as appropriate. Once the Install button has been pressed, and the files have been successfully installed, the final screen will appear, as shown in **Figure 2.6**.

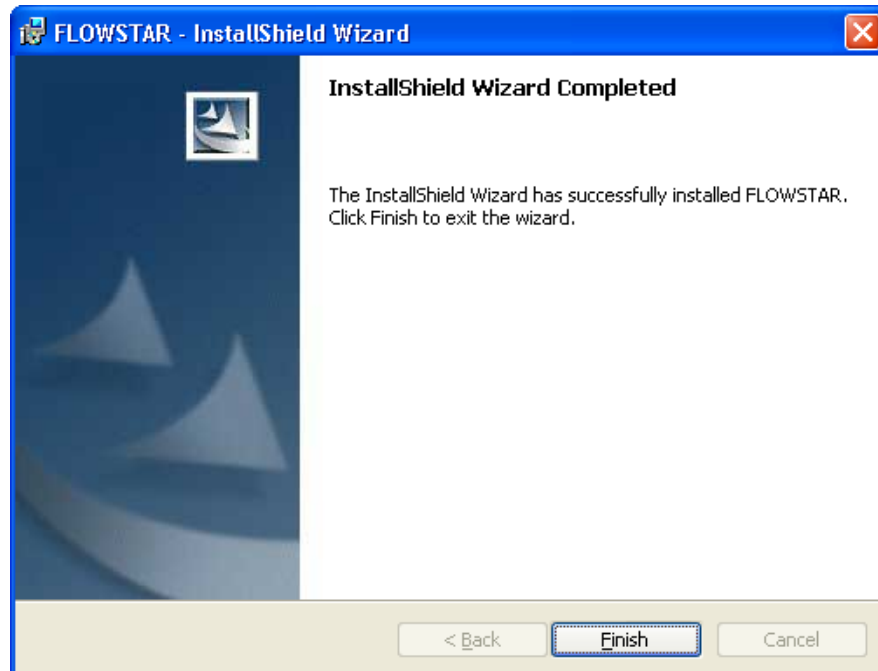


Figure 2.6 - The Installation Wizard Completed screen.

Step 7 Click Finish to complete the installation. For your convenience, the installation procedure automatically puts a shortcut to FLOWSTAR on your Windows desktop.

Step 8 If you are installing FLOWSTAR for the first time, it is important that you also install the FLOWSTAR licence (which will have been emailed to you separately). To do this, place the file *flowstar.lic* in the <install_path> directory.

If you are installing FLOWSTAR as an upgrade, copy *flowstar.lic* from the installation directory of the previous version to the installation directory of the new version.

Step 9 Restart your computer: you are now ready to use the model.

2.3 Removing FLOWSTAR from your computer

To remove FLOWSTAR from your computer, click on the Windows Start button, and select Control Panel. Double-click on the Add/Remove Programs icon. Select FLOWSTAR from the list of installed programs and click on Remove. This will uninstall FLOWSTAR.

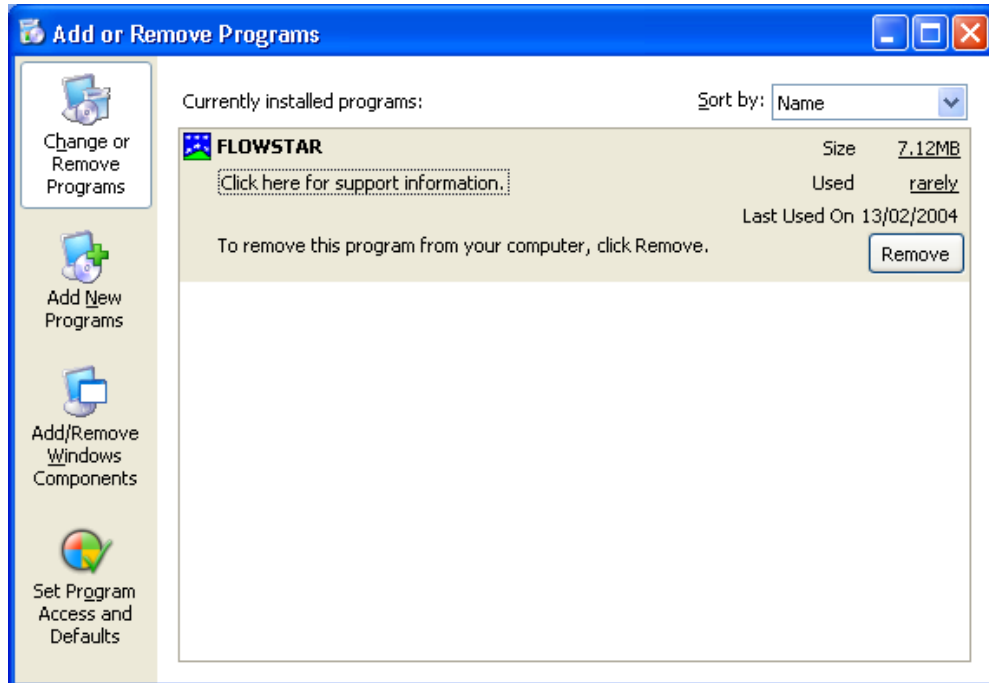


Figure 2.7 - The Add/Remove Programs screen

2.4 Getting around the interface

2.4.1 Mouse buttons

Unless otherwise stated, mouse instructions refer to the left button. If the mouse options have been used to reverse the mapping (e.g. because you are left-handed), the right mouse button should be used instead.

2.4.2 Keyboard access

All mouse instructions in this manual can be reproduced using keystrokes. A brief guide to these keystrokes is given in **Table 2.1**.

Moving the cursor between data entry boxes

TAB	Moves the cursor forward through data entry boxes or buttons
SHIFT + TAB	Moves the cursor backwards through data entry boxes and buttons
RETURN	'Enters' or accepts the current data page or executes the action of a highlighted button
SPACEBAR	Selects or deselects the highlighted option

Entering data in a box

DELETE	Deletes the character immediately to the right of the cursor
BACKSPACE	Deletes the character immediately to the left of the cursor
← arrow	Moves the cursor one space to the left in the current box
→ arrow	Moves the cursor one space to the right in the current box
SHIFT + arrow	Begins highlighting characters in the direction of the arrow (see above)

Highlighted text

DELETE	Deletes all highlighted characters
(Type)	Typing text replaces the highlighted text with new text

Radio buttons

← arrow	Moves the cursor up through the radio buttons for the current item
→ arrow	Moves the cursor down through the radio buttons for the current item

Table 2.1 – Keystrokes to enable you to move through the FLOWSTAR interface.

Access Keys

Also known as shortcut keys, these are combinations of keys that perform some of the main commands. For example, menu commands that have one letter underlined are accessible by holding down the **ALT** key and then typing the underlined letter. For example, the menu command Open... located on the File menu, may be executed by typing **ALT + F** and then **ALT + O**.

SECTION THREE: INPUT

3.1 Introduction

Setting up a modelling problem for FLOWSTAR requires the user to input data specifying the terrain, meteorological conditions and details of the output required. These data are required for every FLOWSTAR run and are input on a set of three screens.

This section provides users with an overall guide to the FLOWSTAR interface, including details of all the input data.

Section 3.1 summarises the general features of the interface, including the menu options, while Sections 3.2 to 3.4 give detailed descriptions of the three input screens. Section 3.5 describes how to save the input data and run the model. Three example input files are provided with the model – these are described in Section 3.6.

3.1.1 Main menu options

The menu bar has five headings (see **Figure 3.1**):

File
Run!
Results
Utilities
Help

Some menu headings have drop-down lists of options. For example, the File menu options list is shown in **Figure 3.1**.

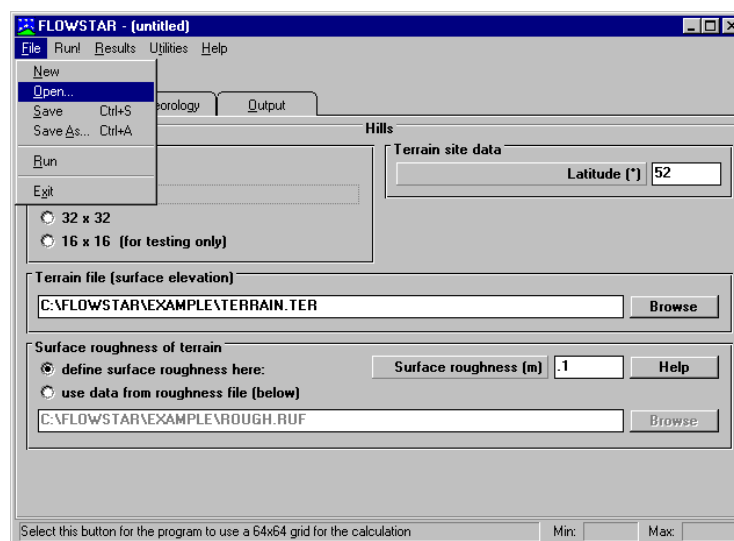


Figure 3.1 – The File menu from the menu bar in FLOWSTAR.

The menu items have the following options and roles.

<u>F</u> ile	<u>N</u> ew	Resets the parameters in the <i>.fpl</i> file to their defaults values.
	<u>O</u> pen	Allows the user to open a previously saved parameter file (see Figure 3.2).
	<u>S</u> ave	Saves the current parameters under the current file name.
	Save <u>A</u> s...	Saves the current parameters with a user specified file name.
	<u>R</u> un	This checks the validity of the input data and runs the FLOWSTAR code using the current parameter file. (The Run! main menu item may also be used.)
	<u>E</u> xit	Quits FLOWSTAR.
Run!		This runs the FLOWSTAR code using the current <i>.fpl</i> file.
<u>R</u> esults	<u>C</u> ontour Plot...	Utility to produce contour plots of mean velocity and turbulence and vector plots of horizontal wind velocity.
	<u>N</u> umerical...	Opens WordPad to view and edit numerical output. (Users may prefer to use Excel , as the numerical output files are in comma-separated format.)
<u>U</u> tilities	Terrain Converter...	Allows the user to prepare a terrain file from OS Data (see Appendix B).
	<u>S</u> urfer...	Launches Surfer plotting package (if the user has Surfer installed on the same machine).
<u>H</u> elp	<u>O</u> btaining Technical Support...	Shows contact details for the FLOWSTAR helpdesk, and detailed model version information.
	<u>A</u> bout...	Shows model version number and system requirements.
	<u>L</u> icence details...	Shows licensee and licence number of the model.

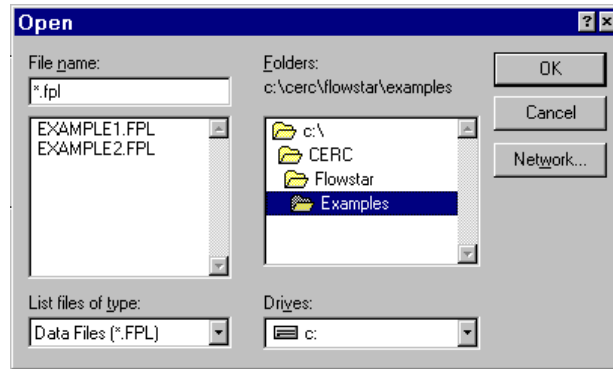


Figure 3.2 – The Open dialogue box.

3.1.2 Input screens

There are three input screens associated with a FLOWSTAR model run. Data must be entered into each of these screens for every run that is set up.

The three screens:

<u>H</u> ills	Parameters describing the general site details.
<u>M</u> eteorology	Parameters describing met. conditions.
<u>O</u> utput	Here the user selects the output required.

Full details of the data to be entered in each screen are given in Sections 3.2-3.4.

Although the data entered into the basic screens are not completely independent of each other, they may be entered in any order. However, it is advisable to enter the data in the screen order from left to right on the interface, namely Hills, Meteorology and Output.

3.1.3 Moving around the FLOWSTAR interface

To move between the input screens simply click on the tabs with the mouse or press the **Alt** key and the underlined letter on each tab (e.g. to select the Meteorology screen, press **Alt + M**). Further details are given in Section 2.3.

Options and variables shown in grey in the interface are not used by the model in the input file currently loaded, e.g. when a particular combination of model options is not permitted.

3.1.4 Help information

At the bottom of each FLOWSTAR screen there is a help line, which contains information on the parameter corresponding to the current cursor position. When the cursor lies in the data entry box for a numerical parameter, the maximum and minimum values for that parameter are shown at the bottom right of the screen.

3.2 Hills

On the Hills screen (Figure 3.3), the following options should be selected as required.

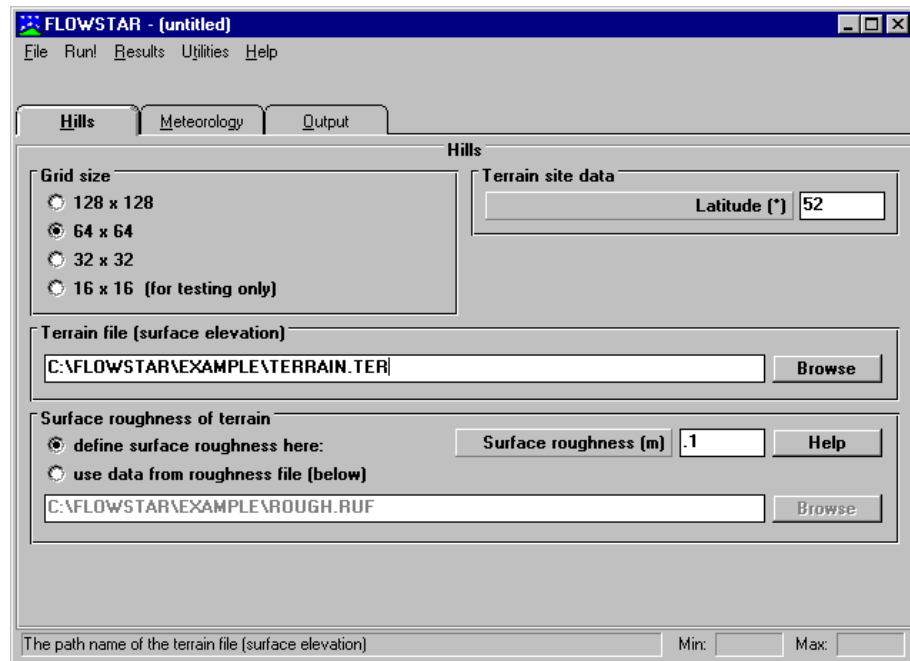


Figure 3.3 – The Hills screen in FLOWSTAR.

- (i) Terrain file (surface elevation) – here the user selects the file defining the complex terrain. In the box, type the full path name of the required terrain file, or use the **Browse** button to find existing *.ter* files.

An example *terrain.ter* file describing a bell-shaped hill is supplied in `<install_path>\data`. It may be edited to create new *.ter* files using a desktop editor. The file is in a simple column format, separated by spaces or commas. There are four columns of data. The first column is a counter and the remaining three are the X and Y co-ordinates of the terrain data points (in metres) and the height of the terrain (in metres). The maximum number of data points that may be included in a *.ter* file is 16500. The points do not need to be regularly spaced, but the area described should be rectangular, and aligned west-east and south-north. Appendix B provides further details of how to create new terrain files, and how to visualise terrain data in Surfer.

- (ii) **Grid Size** – the following choices of internal calculation grid sizes are offered: 128 x 128 (for large domains or terrain of a nature that will not be resolved by a coarser grid), 64 x 64, 32 x 32 and 16 x 16 (for testing only).
- (iii) **Latitude** - here the latitude of the terrain area should be entered.
- (iv) **Surface roughness data** - the user must choose from the following options:
 - (a) define surface roughness here
 - (b) use data from roughness file (below)

If option (a) is selected, a single value of surface roughness is used for the whole terrain area. This is entered in the Surface roughness box. Option (b) should be chosen if local variations in surface roughness occur (see iv). If the terrain is flat but there are significant variations in roughness, the model can be run with a terrain file describing flat terrain, but a *.ruf* roughness file describing the different land uses.

The values in either the terrain or the roughness file should not all be equal, or the program will fail. To model 'flat' terrain, the terrain file should include at least one point that is at a different height from the remaining points.

- (v) **Surface roughness file** – Type the full path name of the required roughness file, or use the Browse button to find existing *.ruf* files. An example file, *roughnes.ruf*, is supplied in *<install_path>\data* and may be edited as above to create new *.ruf* files. An easy way to create a roughness file is to edit the Z values of the terrain file being used so that the same domain, with the same X and Y coordinates, is used for both files. This can be carried out using a spreadsheet package such as Excel.

This box is only active if the Use data from roughness file (below) option has been selected. Using surface roughness values from a file increases calculation time.

3.3 Meteorology

A detailed description of the different types of meteorological data that may be used with FLOWSTAR is given in Appendix A.

The name of the file from which the met. data are to be read must be given by the user (**Figure 3.4**). Clicking Browse displays the directory structure and lets the user select prepared met. files which, by convention, have the extension *.met*.

Additional data are entered just below the file name. These are

- the Height of recorded wind (m) (usually 10 m)
- whether or not Met. data are hourly sequential (for further explanation of these terms, see Appendix A)
- the surface roughness at the met. site (m) (if different from the terrain site)

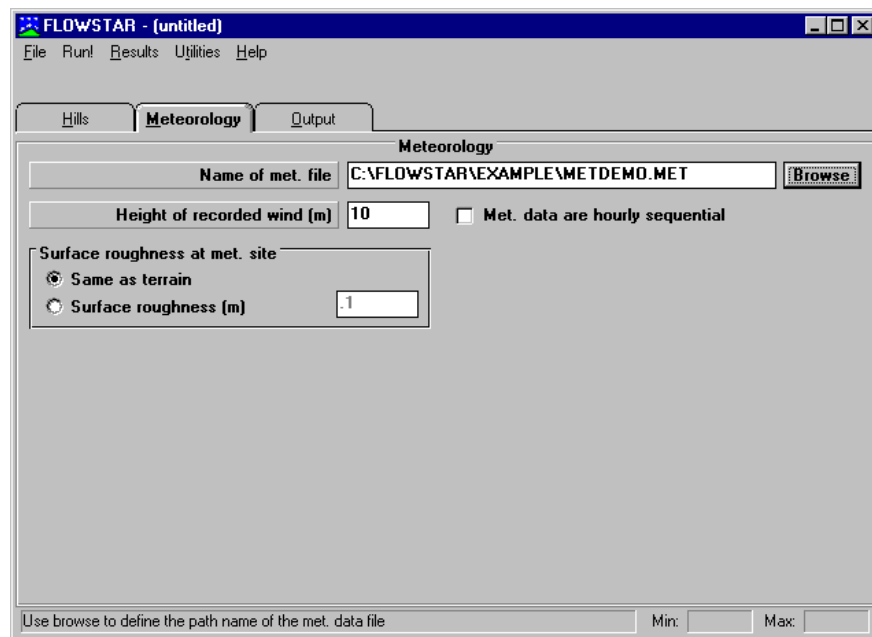


Figure 3.4 – The Meteorology screen in FLOWSTAR

3.4 Output

The output given by FLOWSTAR consists of wind flow and turbulence data. Components of the wind and turbulence in the horizontal and vertical directions are given. Output can be given on a regularly spaced grid covering the same area as the input terrain data, or at locations specified by the user.

The type of output required and the height (or heights) of output are selected by the user on the Output screen (**Figure 3.5**).

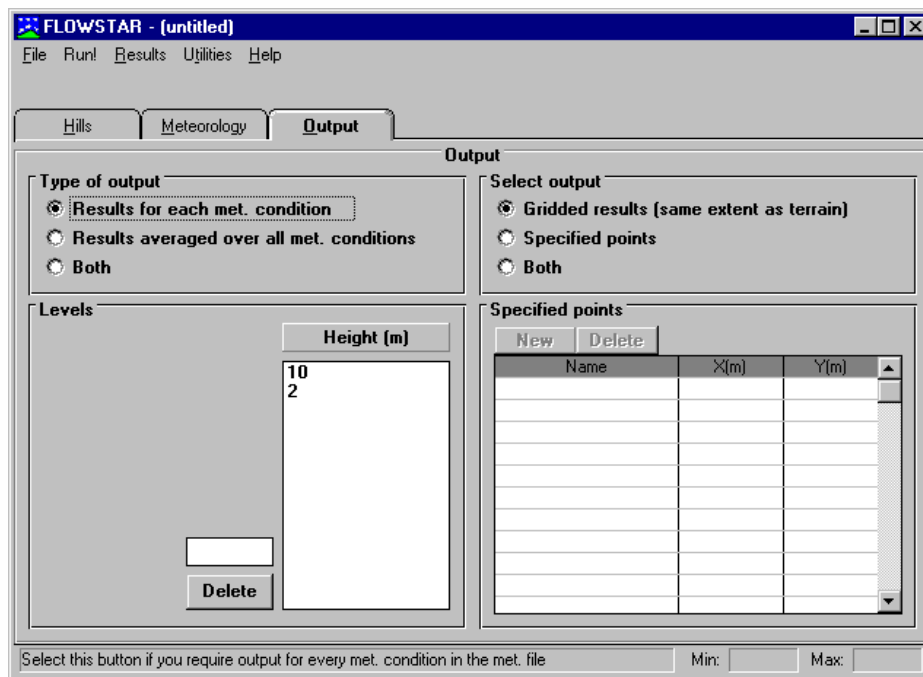


Figure 3.5 – The Output screen in FLOWSTAR

- (i) **Type of output**
FLOWSTAR calculates two types of output.
- Firstly, flow and turbulence data are calculated separately for each met. condition (i.e. a full set of output will be given for each line of data in the met. file). This is useful when investigating the impact of particular met. conditions. To select this type of output, click Results for each met. condition.
 - Secondly, mean flow and turbulence data, averaged over all the input met. conditions, are calculated. These data are useful in assessing, for example, where on average the wind is strongest during the year, or the variation over the terrain of the direction of the prevailing wind. To select this type of output, click Results averaged over all met. conditions.

It is also possible to select both types of output, by selecting Both.

The data listed in the output files for each type of output are slightly different. For full details, please see the description of the output files in Section 4.1. Note also that, since the output files can be quite large, if Results for each met condition are selected then results will only be given for the first 24 lines of data in the met. file.

(ii) Levels

Output is given at up to 50 heights above local terrain. The heights are selected by the user in the Levels box. To input a height, click on the small text box above the Delete button and type the height in metres, then press the **Space** bar. This will move the value into the Height list on the right. To delete a height, click on it in the Height list then click on the Delete button.

All heights should be greater than 1.3 times the maximum surface roughness length at the terrain site, i.e. greater than 1.3 times the value of Surface roughness in the Hills screen if a constant value of surface roughness is used, or greater than 1.3 times the maximum surface roughness in the roughness file, if a roughness file is used. If a height lower than this value is input, no output will be given at that height.

(iii) Select output

Output can be given at points on a regular grid, or at specified points.

- Gridded results are given at points on a regular grid that covers the same area as the terrain data. The grid spacing depends on the Grid size setting selected by the user on the Hills screen. For example, if 32 x 32 is selected, the output grid will contain 32 points in the X (west-east) direction and 32 points in the Y (south-north) direction.
- To obtain details of the flow and turbulence at a particular location, select Specified points and enter the coordinates into the table (see (iv)).

It is also possible to select both types of output, by selecting **Both**.

(iv) Specified points

To enter a specified receptor point to the table, first ensure that the Specified points option is selected. Click on the New button, and a default set of X, Y coordinates is entered, with a default name. Click on each cell in turn to edit the default name and change the default value to your chosen coordinates. Up to 50 specified points may be entered in any one run.

3.6 Example files

Three example files are provided with the model. The user may find it useful to open these in the interface, run the model and look at the output. (Note that a general description of FLOWSTAR output files is given in Section 4.) A brief description of the example files is given below.

Example1.fpl

- Bell-shaped hill (as in the example terrain file *terrain.ter*)
- Surface roughness data read from the example file *roughnes.ruf*
- Individual flow and turbulence fields calculated for 3 met. conditions (convective, neutral and stable conditions)
- Output given on a 64 by 64 grid, at 2m and 10m above the terrain

Example2.fpl

- Bell-shaped hill (as in the example terrain file *terrain.ter*)
- Constant surface roughness of 0.1m
- Average flow and turbulence fields calculated for one day of met. data
- Output given on a 32 by 32 grid, at 2m, 10m and 100m above the terrain

Example3.fpl

- Bell-shaped hill (as in the example terrain file *terrain.ter*)
- Constant surface roughness of 0.1m
- Individual flow and turbulence parameters calculated for 3 met. conditions (convective, neutral and stable conditions)
- Output given at two specified points, one upstream and one downstream of the hill summit, at intervals of 10m up to 100m above the terrain

SECTION FOUR: OUTPUT

4.1 Output files

During a FLOWSTAR model run, a number of output files are created. These files contain the results of the run and are stored in the same directory as the *.fpl* file used in the run. To display model results, the output files can be opened using the output utilities described in Sections 4.2-4.3.

All output files for a model run have the same file stem but a different extension. For instance, the output files produced for the *.fpl* file *example.fpl* would be:

<i>example.log</i>	Details of the run
<i>example.mop</i>	Input and calculated meteorological parameters
<i>example.w01, .w02 etc</i>	Gridded flow field results for each met. condition
<i>example.t01, .t02 etc</i>	Gridded turbulence results for each met. condition
<i>example.wlt</i>	Gridded averaged flow field results
<i>example.tlt</i>	Gridded averaged turbulence results
<i>example.zst</i>	Specified points flow field and turbulence results for each met. condition
<i>example.zlt</i>	Specified points averaged flow field and turbulence results

Full descriptions of each output file are given below.

.log

This file contains a log of the run detailing

- the date and time of the start and end of the run
- the model parameters entered in the interface
- program messages (particularly useful if the model cannot complete the run for some reason)
- a summary of the met data, including the number of lines of data the model was able to use

.mop

This file contains the meteorological input parameters and calculated meteorological output values for each line of met. data in the met. file. The frequency of occurrence of each condition is also reported. The input parameters are in the left-hand columns of the file, and the calculated output parameters in the right-hand columns.

.w01, .w02 etc

These files contain the flow field for met. line 1, met. line 2 etc. over the area covered by the input terrain data. Values are given on a regularly spaced grid, at the heights selected in the interface. Note that these files are only created if the user opts to calculate gridded results for each met condition, and are only created for the first 24 lines of met. data.

Each output file contains 10 columns of data:

X(m)	X co-ordinate of output point (metres)
Y(m)	Y co-ordinate of output point (metres)
Z(m)	Height above terrain of output point (metres)
U(m/s)	Component of wind velocity in west-east direction
V(m/s)	Component of wind velocity in south-north direction
W(m/s)	Vertical component of wind velocity (relative to sea level)
Ux(m/s)	Longitudinal component of wind velocity (i.e. in the direction of the upstream wind; the direction specified for the wind in the meteorological data)
Uy(m/s)	Transverse component of wind velocity (i.e. perpendicular to the direction of the upstream wind)
Angle	Wind direction (degrees measured anticlockwise, 0° = wind from west)
Magnitude	Magnitude of horizontal wind velocity ($= \sqrt{U^2 + V^2}$)

.t01, .t02 etc

These files contain flow field turbulence data for met. line 1, met. line 2 etc. over the region covered by the input terrain data. Values are given on a regularly spaced grid, at the heights selected in the interface. The files are only created if the user opts to calculate gridded results for each met condition, for the first 24 lines of met. data. Each file contains 6 columns of data:

X(m)	X co-ordinate of output point (metres)
Y(m)	Y co-ordinate of output point (metres)
Z(m)	Height above terrain of output point (metres)
Sig-U(m/s)	Longitudinal turbulence σ_u
Sig-V(m/s)	Transverse turbulence σ_v
Sig-W(m/s)	Vertical turbulence σ_w

.wlt

This file contains the mean flow field, averaged over all the lines of met. data. The file is only created if the user opts to calculate gridded averaged results. The file contains 10 columns of data:

X(m)	X co-ordinate of output point (metres)
Y(m)	Y co-ordinate of output point (metres)
Z(m)	Height above terrain of output point (metres)
U(m/s)	Component of the mean wind velocity in west-east direction
V(m/s)	Component of mean wind velocity in south-north direction
W(m/s)	Vertical component of mean wind velocity (relative to sea level)

Mean horizontal wind speed (m/s)

Mean value of horizontal wind speed $\sqrt{\overline{U^2} + \overline{V^2}}$

Magnitude of mean horizontal wind vector (m/s)

Magnitude of the mean horizontal wind vector $\sqrt{\overline{U^2} + \overline{V^2}}$

Angle

Angle between North and the direction the mean horizontal wind vector approaches from, measured in degrees

Magnitude of mean horizontal wind vector (m/s)

Magnitude of the mean horizontal wind vector (Note that this column appears twice in the file – this is for use by the contour/vector plotting tool, described in Section 4.3.)

For a full description of how these data are calculated, please see the Technical Summary, section 5.4.

.ilt

This file contains the mean turbulence field, averaged over all the lines of met. data. The file is only created if the user opts to calculate gridded averaged results. The file contains 6 columns of data:

X(m)	X co-ordinate of output point (metres)
Y(m)	Y co-ordinate of output point (metres)
Z(m)	Height above terrain of output point (metres)
Sig-U(m/s)	Mean longitudinal turbulence σ_u
Sig-V(m/s)	Mean transverse turbulence σ_v

Sig-W(m/s) Mean vertical turbulence σ_w

For a full description of how these data are calculated, please see the Technical Summary, section 5.4.

.zst

This file contains the mean flow and turbulence parameters at each point entered by the user in the Specified points table, for each met. condition. Each output file contains 17 columns of data:

Year	Year of the current line of met. data
Day	Julian day number of the current line of met. data
Hour	Hour of the current line of met. data (between 0 and 23)
Receptor name	Name of the specified point, as entered in the table
X(m)	X co-ordinate of specified point (metres)
Y(m)	Y co-ordinate of specified point (metres)
Z(m)	Height above terrain of output (metres)
U(m/s)	Component of wind velocity in west-east direction
V(m/s)	Component of wind velocity in south-north direction
W(m/s)	Vertical component of wind velocity (relative to sea level)
Ux(m/s)	Longitudinal component of wind velocity (i.e. in the direction of the upstream wind; the direction specified for the wind in the meteorological data)
Uy(m/s)	Transverse component of wind velocity (i.e. perpendicular to the direction of the upstream wind)
Angle	Wind direction (degrees measured anticlockwise, 0° = wind from west)
Magnitude	Magnitude of horizontal wind velocity ($= \sqrt{U^2 + V^2}$)
Sig-U(m/s)	Longitudinal turbulence σ_u
Sig-V(m/s)	Transverse turbulence σ_v
Sig-W(m/s)	Vertical turbulence σ_w

.zlt

This file contains the mean flow and turbulence parameters at each point entered by the user in the Specified points table, averaged over all met. conditions. Each output file contains 12 columns of data:

Receptor name	Name of the specified point, as entered in the table
X(m)	X co-ordinate of specified point (metres)

Y(m)	Y co-ordinate of specified point (metres)
Z(m)	Height above terrain of output (metres)
U(m/s)	Component of the mean wind velocity in west-east direction
V(m/s)	Component of mean wind velocity in south-north direction
W(m/s)	Vertical component of mean wind velocity (relative to sea level)

Mean horizontal wind speed (m/s)

Mean value of horizontal wind speed $\sqrt{\overline{U^2 + V^2}}$

Magnitude of mean horizontal wind vector (m/s)

Magnitude of the mean horizontal wind vector $\sqrt{\overline{U^2} + \overline{V^2}}$

Sig-U(m/s) Mean longitudinal turbulence σ_u

Sig-V(m/s) Mean transverse turbulence σ_v

Sig-W(m/s) Mean vertical turbulence σ_w

For a full description of how these data are calculated, please see the Technical Summary, section 5.4.

4.2 Viewing numerical data

The FLOWSTAR numerical output files are all in comma-separated format, and are easiest to view using a spreadsheet package such as Microsoft Excel. The output files can also be accessed from the FLOWSTAR interface and viewed in WordPad.

Use of WordPad to view numerical output

Using the FLOWSTAR interface and the default application WordPad, viewing numerical output can be achieved in the following steps.

- 1) Select the Numerical... option from the Results menu.
- 2) The default output file used by this option is the .w01 file. Other output files can be viewed by clicking on the File menu and then clicking on Open...
- 3) Change the file type in the Files of type box to All Documents(*.*).
- 4) Click on the file required, then click Open.

Use of Excel to view numerical output

Using Microsoft Excel, the numerical files can be viewed through the following steps.

- 1) Start Excel.
- 2) Select Open from the File menu.
- 3) Move through directories to locate the relevant directory.
- 4) Type the file name extension of the required output file (e.g. .w01 if searching for *filename.w01*) in the File name box.
- 5) Click on the file you want to open and then click Open. This starts the "Text Import Wizard" (**Figure 4.1**).

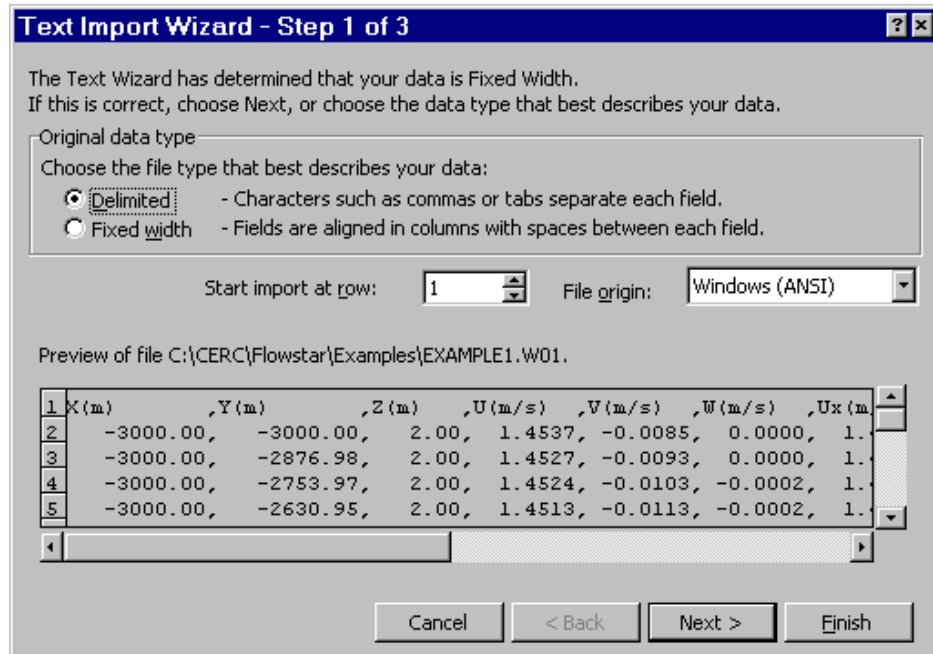


Figure 4.1 – The Excel Text Import Wizard.

- 6) FLOWSTAR output files are comma-delimited so they can be imported easily into many standard packages. From the Text Import Wizard, select the Delimited option and then click on the Next> button to move to the next step (Figure 4.2).

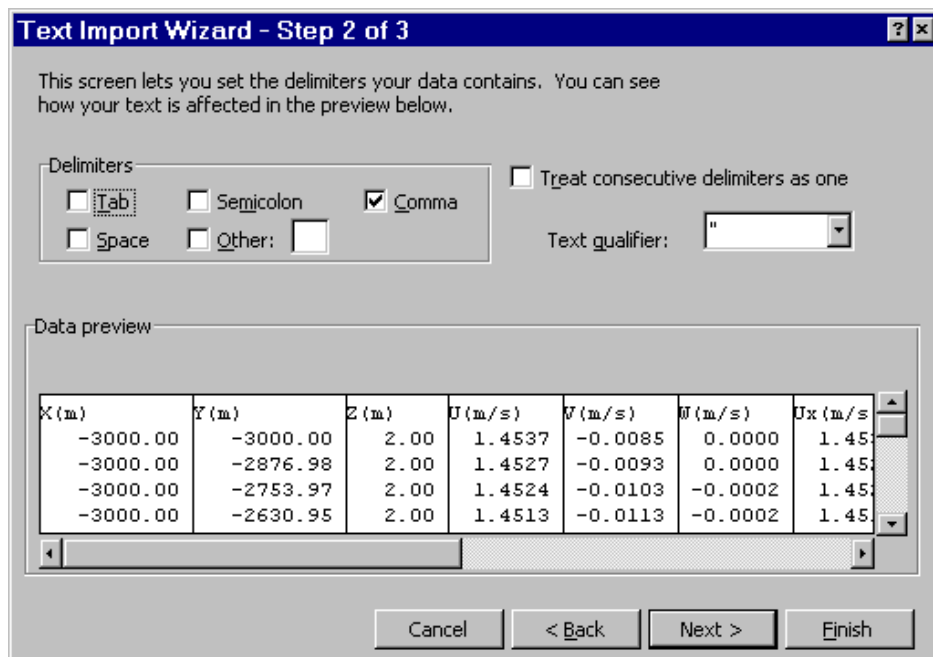


Figure 4.2 – Step 2 of the Excel Text Import Wizard.

- 7) In the Delimiters box, select the Comma check box, and then click on the Next> button to move to the next step (Figure 4.3).

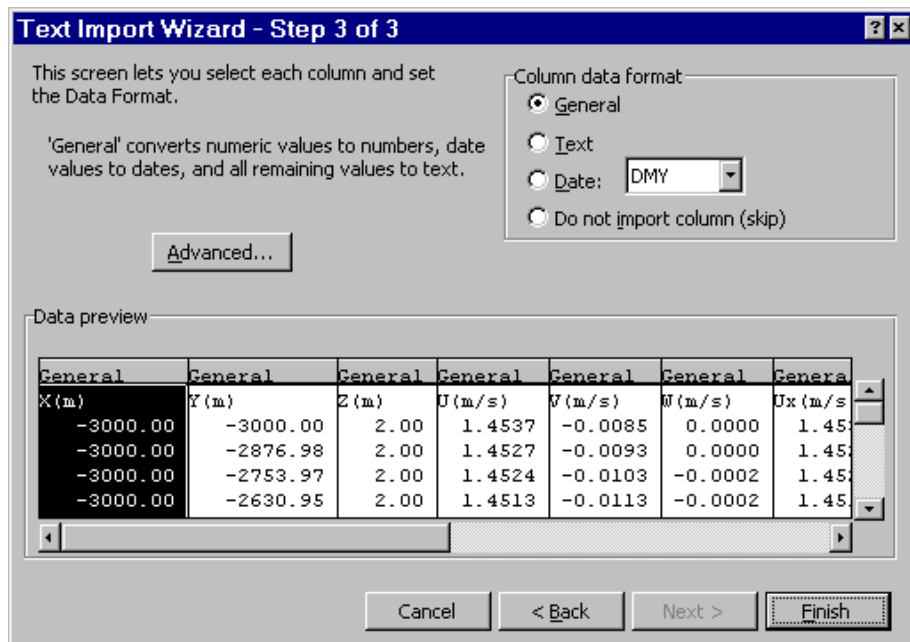


Figure 4.3 – Step 3 of the Excel Text Import Wizard.

- 8) In the Data Preview box, ensure that the file has been properly separated and then click on the Finish button to import the data (Figure 4.4).

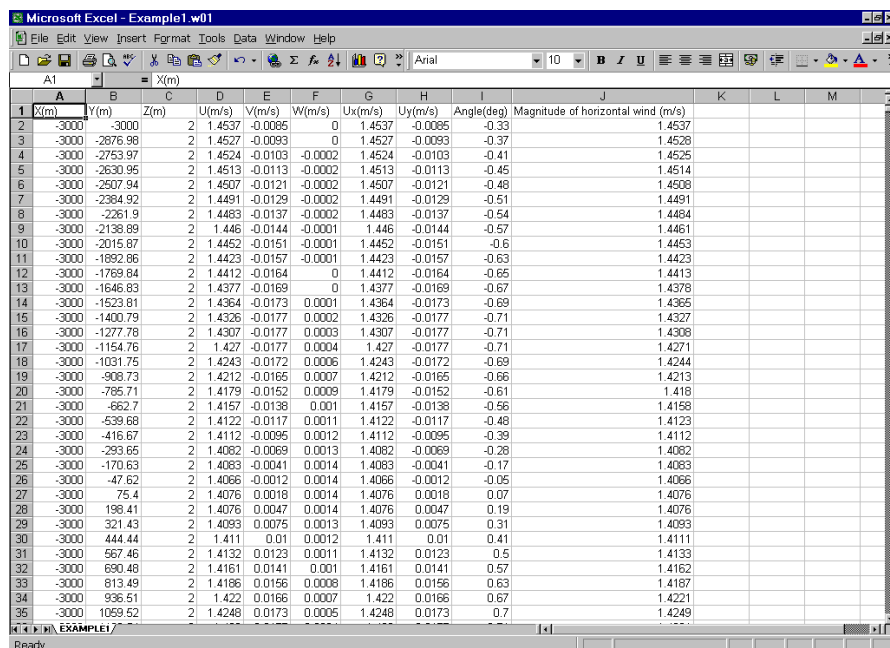


Figure 4.4 – FLOWSTAR output data imported into Excel.

If the column headings are not visible because the columns are too narrow, select all the columns containing data and use **Format, Column, Auto Fit Selection** to increase the column widths to fit the longest entry in each column.

4.3 Contour and vector plotting

Contour plots and vector plots of the wind and turbulence fields may be created in Surfer using the Flowfield Plotter. To launch the Flowfield Plotter, select Contour Plot... from the Results menu. The Flowfield Plotter is shown in **Figure 4.5**. The processes of creating contour plots and vector plots are described in Sections 4.3.1 and 4.3.2.

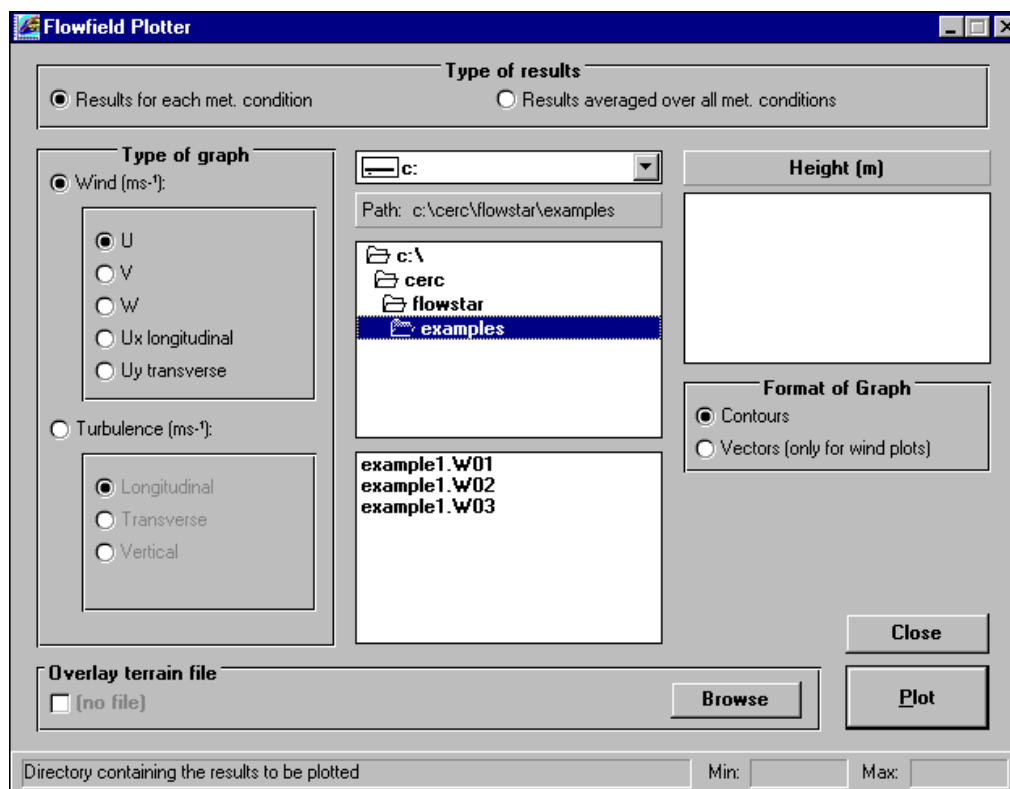


Figure 4.5 – Flowfield Plotter

4.3.1 Contour plots

First, choose whether to plot results calculated for each met. condition, or results averaged over all met. conditions by selecting the appropriate option in the Type of Results box at the top of the screen.

To create a contour plot, select Contours in the Format of Graph box on the right-hand side of the screen. The data that can be plotted are selected in the Type of graph box and are described below.

Wind (ms^{-1})

U	Component of wind velocity in west-east direction
V	Component of wind velocity in south-north direction
W	Vertical component of wind velocity (relative to sea level)

If Results for each met. condition is selected, the next two wind options are:

Ux longitudinal	Longitudinal component of wind velocity, i.e. in the direction of the upstream wind (the direction specified for the wind in the meteorological data)
Uy transverse	Transverse component of wind velocity, i.e. perpendicular to the direction of the upstream wind

If Results averaged over all met. conditions is selected, the next two wind options are:

Mean wind	Mean horizontal wind speed
Mean vector magnitude	Magnitude of the mean horizontal wind vector

Turbulence (ms^{-1})

Longitudinal	Turbulence parameter of longitudinal wind component
Transverse	Turbulence parameter of transverse wind component
Vertical	Turbulence parameter of vertical wind component

Select the appropriate data to plot in the Type of graph box, select an output file and then select a height from the Height box. Note that these heights are measured from the surface of the terrain. Click Plot to display the contour plot in Surfer. An example is shown in **Figure 4.8**.

It is possible to overlay the contour plot on a plot of the terrain data. To do this, select Overlay terrain file, then browse for the terrain file, before clicking Plot.

4.3.2 Vector plots

The horizontal wind (i.e. the vectors (U,V)) can also be displayed as a vector plot. Select Wind (ms^{-1}) in the Type of graph box, then Vectors (only for wind plots) in the Format of Graph box. Select an output file and height, and click on Plot to display the vector plot.

At this stage you may see that the arrows on the vector plot are too large to resolve the flow field properly. This is due to a problem with Surfer. To correct the arrow size:

- double click on the vector plot to display the VectorPlot Properties screen (**Figure 4.6**)

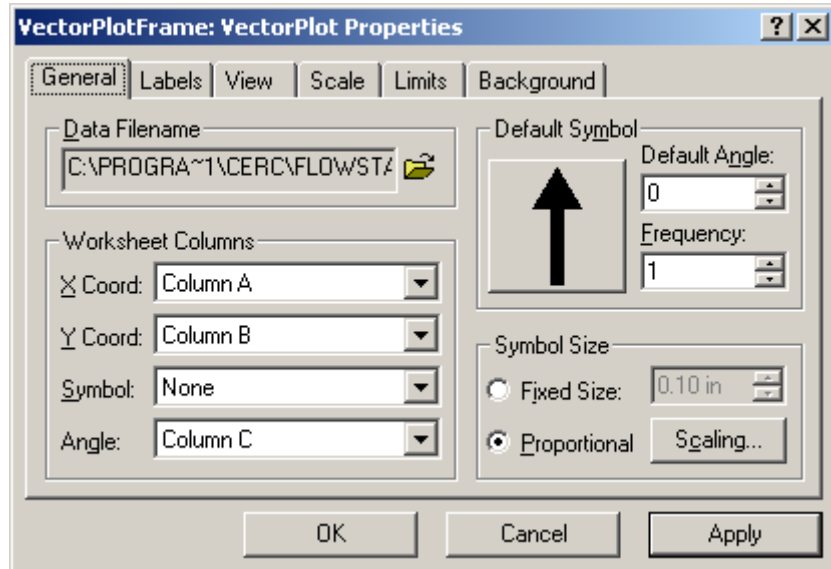


Figure 4.6 – The VectorPlot Properties screen in Surfer

- from the General tab, click on Scaling... then un-tick and tick the Use Data Limits option
- click OK twice to return to the plot.

The arrows should then be resized. Note that the arrow size is scaled using the magnitude of the wind.

Again the plot may be overlaid on a plot of the terrain data, as shown in **Figure 4.9**.

c:\cerc\flowstar\examples\EXAMPLE1.W02

Contour plot: Component of mean wind from West (U), at height 10m

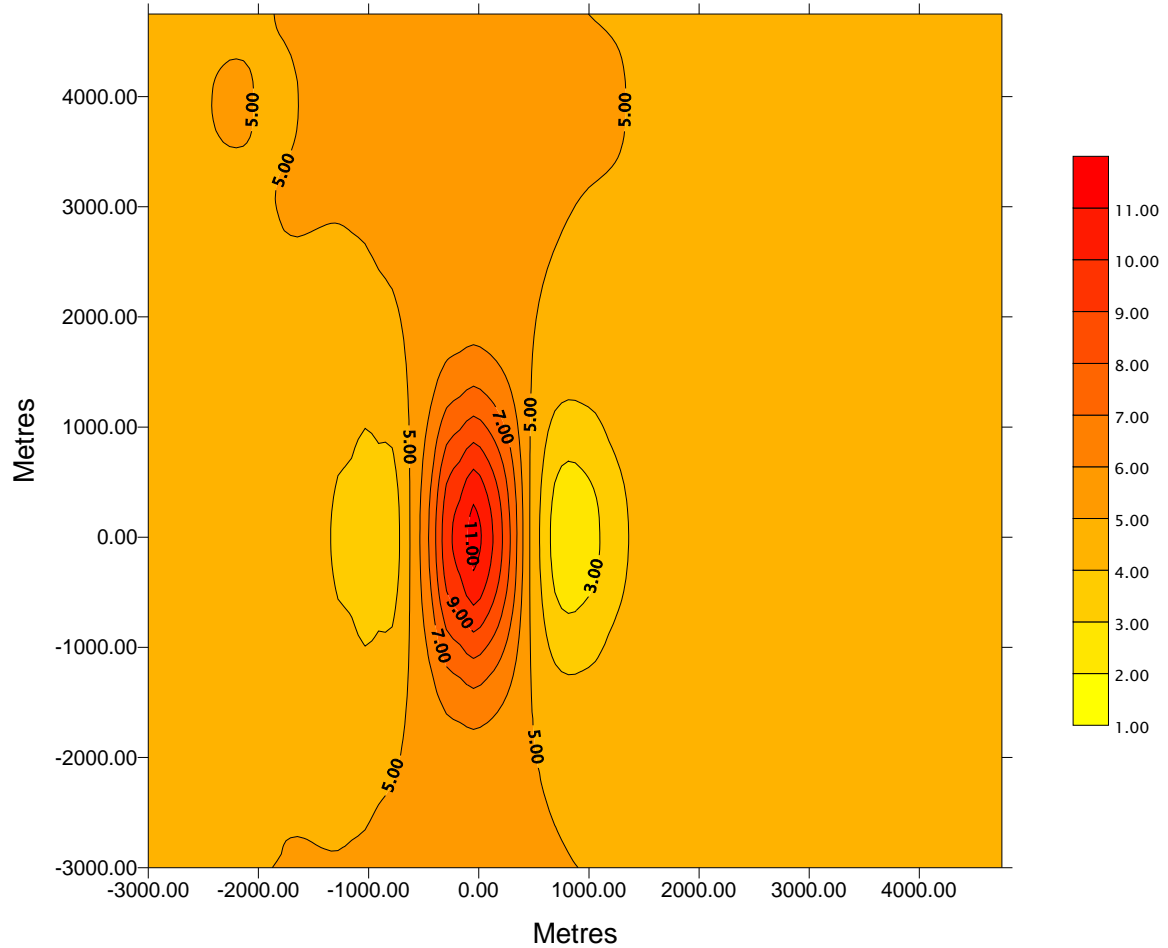


Figure 4.8 – Example flow field contour plot.

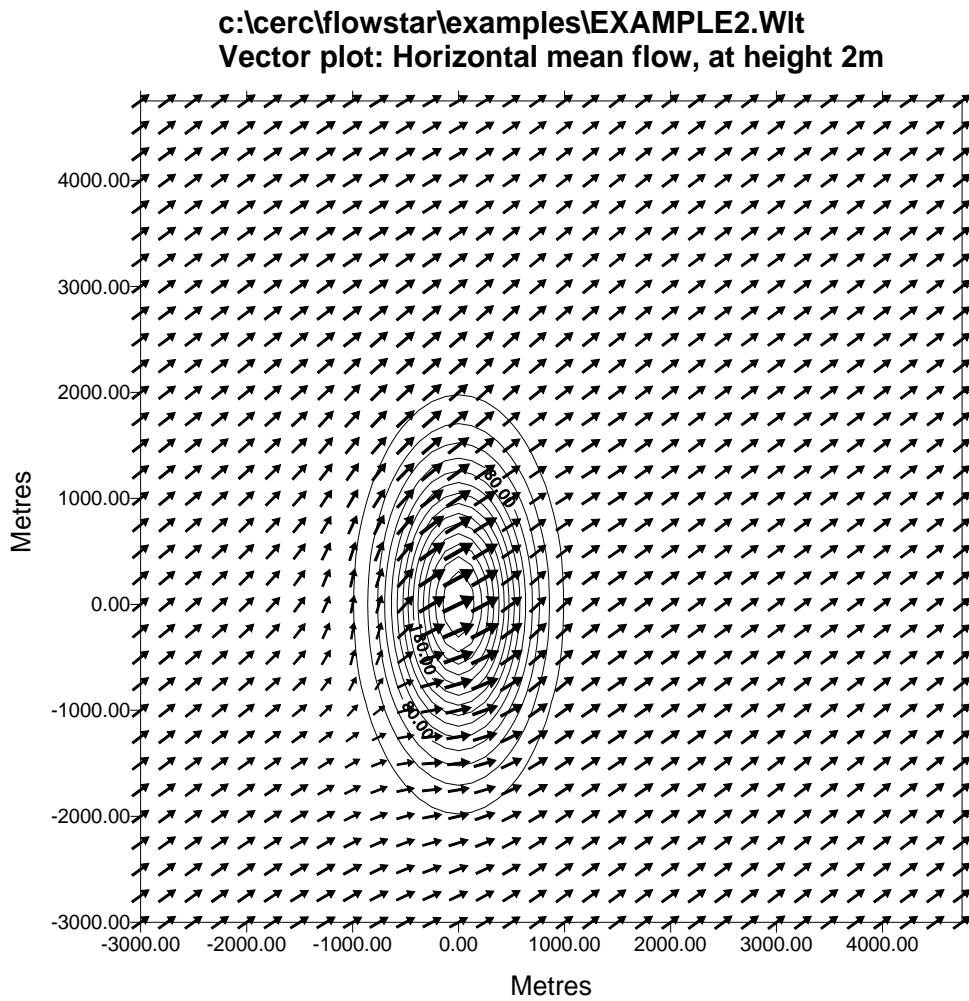


Figure 4.9 – Example flow field vector plot.

SECTION FIVE: TECHNICAL SUMMARY

This section is intended to provide a summary of the mathematical and physical background to FLOWSTAR. The majority of material in this section is taken from the ADMS 4 Technical Specification documentation (CERC, 2010), to which readers should refer for full details. Any differences between the material in this documentation and the section below (updated May 2011) are noted. In this Technical Summary, the following topics are covered.

- (1) Meteorological input module
- (2) Parameterisation of the boundary layer
- (3) Complex terrain
- (4) Long term averages

5.1 Meteorological Input Module

5.1.1 Introduction

Appendix A describes the types of meteorological data that can be input to FLOWSTAR. For all the data types each line of input data describes the meteorological conditions for one or more hours, the conditions being assumed to be fixed for any given hour. The Met Input module reads the data and uses the pre-processing algorithms to estimate values of the various meteorological quantities required for running the model.

Data may be in the form of a chronological record. These data are termed hourly *sequential*. Other data may have a certain weight or frequency associated with each line of met. data. Such data are usually non-chronological and are termed *statistical* as they have been statistically analysed. It is also possible that the data are neither sequential nor statistical, but some more general collection of one or more met. conditions.

5.1.2 Input

The met. input data set can contain a variety of input met. parameters.

The complete list of possible inputs is shown in **Table 5.1**. The first three columns are alternative forms of the variable names that may be used in creating met. data files. As FLOWSTAR matches the string to identify a variable the user may want to use short versions of the variable names (Columns 1 and 3) in order to avoid making errors in typing. Names from different lists may be used in the same met file,

e.g. using U for wind speed and CLOUD for cloud cover in the same file is fine.

It is likely that the two most common types of input data will be sequential data (or data for a single hour) giving wind speed, direction, cloud cover, time of day, time of year, temperature and possibly precipitation and sea surface temperature, and statistical data, comprising wind speed, direction, surface sensible heat flux, boundary layer height and precipitation. Such data are supplied by the Met. Office for the main UK met. stations.

Short name	Long name	Abbreviated name	Units
WIND SPEED	WIND SPEED	U	m/s
UG/USTAR	GEOSTROPHIC WIND SPEED/FRICTION VELOCITY	UGSTAR	-
WIND DIRN	WIND DIRECTION (DEGREES)	PHI	degrees
DIRN CHANGE	GEOSTROPHIC MINUS SURFACE WIND DIRECTION (DEGREES)	DELTAPHI	degrees
HEAT FLUX	SENSIBLE HEAT FLUX	FTHETA0	W/m ²
1/LMO	1/MONIN-OBUKHOV LENGTH	RECIPLMO	m ⁻¹
BL DEPTH	BOUNDARY LAYER DEPTH	H	m
CLOUD	CLOUD AMOUNT (OKTAS)	CL	oktas
SOLAR RAD	INCOMING SOLAR RADIATION	SOLAR RAD	W/m ²
TEMPERATURE	TEMPERATURE (C)	T0C	°C
N ABOVE BL	BUOYANCY FREQUENCY ABOVE BOUNDARY LAYER	NU	s ⁻¹
DELTA THETA	TEMPERATURE JUMP ACROSS BOUNDARY LAYER TOP	DELTATHETA	°C
SIGMA THETA	SIGMA THETA (DEGREES)	SIGMATHETA	degrees
HOUR	HOUR	THOUR	-
DAY	DAY	TDAY	-
YEAR	YEAR	YEAR	-
FREQUENCY	FREQUENCY	FR	-
FREQUENCY FOR MONTHS xx TO xx, HOURS xxxxxx TO xxxxxx (GMT + xxxxxx)	FREQUENCY FOR MONTHS xx TO xx, HOURS xxxxxx TO xxxxxx (GMT + xxxxxx)	MONTHS xx TO xx, HOURS xx TO xx	-

Table 5.1 - Variables that may be input into the met. input module.

Note that the Pasquill-Gifford stability categories cannot be directly input into the model (although of course values of U , ϕ , L_{mo} and h may be), nor are they output. In FLOWSTAR the boundary structure is characterised by the two parameters, h and L_{MO} . Values of these parameters corresponding *approximately* to the Pasquill-Gifford categories are shown in the data file *r91a-g.met* and below in **Table 5.2**.

U (ms^{-1})	L_{MO} (m)	$1/L_{MO}$ (m^{-1})	h (m)	h/L_{MO}	P-G Category
1	-2	-0.5	1300	-650	A
2	-10	-0.1	900	-90	B
5	-100	-0.01	850	-8.5	C
5	∞	0	800	0	D
3	100	0.01	400	4	E
2	20	0.05	100	5	F
1	5	0.2	100	20	G

Table 5.2 - Values of wind speed, Monin-Obukhov length (L_{MO}) and boundary layer height (h) which *may* be used to represent Pasquill-Gifford categories A-G.

There is no exact correspondence between the boundary layer parameters (h , L_{MO}) and the Pasquill-Gifford categories since many different values of h and L_{MO} may correspond to one Pasquill-Gifford category.

Stability:	Stable	$h/L_{MO} \geq 1$
	Neutral	$(-0.3 \leq h/L_{MO} < 1)$
	Convective	$h/L_{MO} < -0.3$

The met. data minimum requirement (for the model to run) is:

- wind speed (this would normally be a near surface wind, but could be a geostrophic wind or friction velocity. In each case the height of wind must be entered, which would typically be 10m for the near-surface case and must be 1000m and 0m for the geostrophic and friction velocity cases, respectively)
- wind direction

plus *one* of the following:

- reciprocal of Monin-Obukhov length
- surface sensible heat flux F_{θ_0}
- cloud cover, time of day and time of year

If more than one of the latter three is supplied, they are used in order of preference in the order they are listed above.

If cloud cover, time of day and time of year are the *only* data specified, then it is advisable to add temperature and boundary layer height, if a good estimate is known, to the variables in the *.met* file. If boundary layer height is not known, the estimate for a particular hour will be improved if met. data for all the hours from midnight are included, as the scheme uses the information from previous hours to improve the estimate.

It is preferable to include cloud cover data if available. However, if unavailable, incoming solar radiation may be specified instead. Incoming solar radiation is measured at ground level, as measured by a radiometer, although check with the manufacturer exactly what is measured.

In general, the boundary layer height should always be entered if you think you can provide a better estimate than the met. input module. The module will provide a good estimate when the site is in mid latitudes, e.g. UK, and it is either

- (i) daytime with sequential data stretching back at least to dawn, or
- (ii) night time.

If however, neither (i) nor (ii) apply and you do *not* have information about the boundary layer height, then it is advisable to provide as much information as you have available (e.g. all five of the above met. parameters). This may help the model to estimate boundary layer height by enabling it to estimate the values of heat flux occurring prior to the current hour under consideration. In addition, specifying temperature may also help to improve the module's estimate of the boundary layer height.

Note that FLOWSTAR does not model calm conditions. Any lines of met data for which the wind speed at 10m is less than 0.75m/s will be skipped by the model and output will be given as -999 for that line of met data.

5.1.3 Further input parameters

In addition to the data in the met. input data set, the module also requires certain data that are provided via the interface. These are:

- latitude
- surface roughness at the met. measurement site and the terrain site
- height of recorded wind, i.e. the height above ground at which the wind measurements were made (usually 10m)
- whether the met data are hourly sequential or not

If the met. site is distant from the terrain site, the met. input module presents the option to modify the wind profile at the terrain site by taking account of the surface roughness both at the met. site and the terrain site.

5.1.4 Meteorological pre-processing

The module is called once for each hour's data and uses standard algorithms to calculate the boundary layer meteorological parameters required by the model. Full details can be found in Holtslag and van Ulden (1983) and the ADMS 4 Technical Specification (CERC, 2010). In processing the data, the module checks that the input data are plausible, i.e. that they lie within certain limits. While it is running, messages may be provided giving warnings and notification of errors. Where an error occurs which prevents calculations being done for that particular line, output for that met line will be given as -999.

5.1.5 Meteorological output

The following variables are output by the meteorological input module:

u_*	Friction velocity (ms^{-1})
U_g	Geostrophic wind speed (ms^{-1})
U_g^*	Geostrophic wind speed normalised by the friction velocity
ϕ_0	Surface wind direction (angle from which wind blows in degrees measured clockwise from north, e.g. 270° is a westerly wind) ($^\circ$)
ϕ_g	Geostrophic wind direction (angle from which wind blows in degrees measured clockwise from north) ($^\circ$)
$\Delta\phi$	Geostrophic wind direction minus surface wind direction ($^\circ$)
U	Wind speed - as obtained from the met. input data set (ms^{-1})
ϕ	Wind direction - as obtained from the met. input data set ($^\circ$)
w_*	Convective velocity scale. If $F_{\theta_0} > 0$, $w_* = (g F_{\theta_0} h / \rho c_p T_0)^{1/3}$; if $F_{\theta_0} \leq 0$, $w_* = 0$ (ms^{-1})
F_{θ_0}	Surface heat flux (Wm^{-2})
$1/L_{MO}$	Reciprocal of the Monin-Obukhov length (m^{-1})
h	Boundary layer height (m)
N_u	Buoyancy frequency above the boundary layer (s^{-1})
$\Delta\theta$	Temperature jump across the boundary layer top (K)
T_0^c	Near surface temperature ($^\circ\text{C}$)
σ_θ	Standard deviation of mean wind direction ($^\circ$).

Table 5.3 - Output variables from the meteorological input module.

The data are now available for use by the other modules, in particular the boundary layer structure module.

5.1.6 Limitations

In calculating the boundary layer parameters, it is assumed that the boundary layer is self-similar for a given value of h/L_{MO} . However, users of the model should be aware that there are some situations, such as latitudes near the equator or the poles, where the approximation can lead to significant errors. Full details are given in the ADMS 4 Technical Specification (CERC, 2010).

5.2 Parameterisation of the boundary layer

In FLOWSTAR the boundary layer is characterised by the boundary layer height h and the Monin-Obukhov length L_{MO} and *not* by a Pasquill-Gifford stability category. The Monin-Obukhov length is defined as

$$L_{MO} = \frac{-u_*^3}{\kappa g F_{\theta_0} / (\rho c_p T_0)} \quad (5.1)$$

in which u_* is the friction velocity at the Earth's surface, κ ($= 0.4$) is the von Karman constant, g is the acceleration due to gravity, F_{θ_0} is the surface sensible heat flux, ρ and c_p are, respectively, the density and specific heat capacity of air and T_0 is the near surface temperature.

In unstable or convective conditions, the Monin-Obukhov length is negative. Then, the magnitude of the length is a measure of the height above which convective turbulence, i.e. turbulent motions caused by thermal convection, is more important than mechanical turbulence, generated by friction at the Earth's surface.

In stable conditions the Monin-Obukhov length is positive. Then it is a measure of the height above which vertical turbulent motion is significantly inhibited by the stable stratification.

Figure 5.1 shows the different regions of the boundary layer in terms of the parameters h/L_{MO} and z/h where z is height above the ground. **Figure 5.2** shows the same information but with a dimensional vertical scale, z , the height above the ground. In the different regions of the boundary layer different mechanisms are important in generating turbulence. These are:

- (i) Surface heating or, convectively generated turbulence. The convective eddies increase in energy as they rise through the boundary layer.
- (ii) Turbulence mechanically generated by shearing at the surface.
- (iii) Local shear, for instance at the top of the boundary layer, can be a weak source of turbulence.

This approach to boundary layer stability, whereby the boundary layer structure is defined in terms of two variables, z/L_{MO} and z/h , supersedes the Pasquill-Gifford formulation, and differs crucially from the Pasquill formulation in allowing the variation of boundary layer properties with height to be included. It is difficult to make exact comparisons between the two schemes, however, and **Figures 5.1** and **5.2** show Pasquill-Gifford stability categories corresponding *approximately* to ranges of h/L_{MO} . Note that,

particularly in stable met. conditions, the Pasquill class is not a simple function of h/L_{MO} .

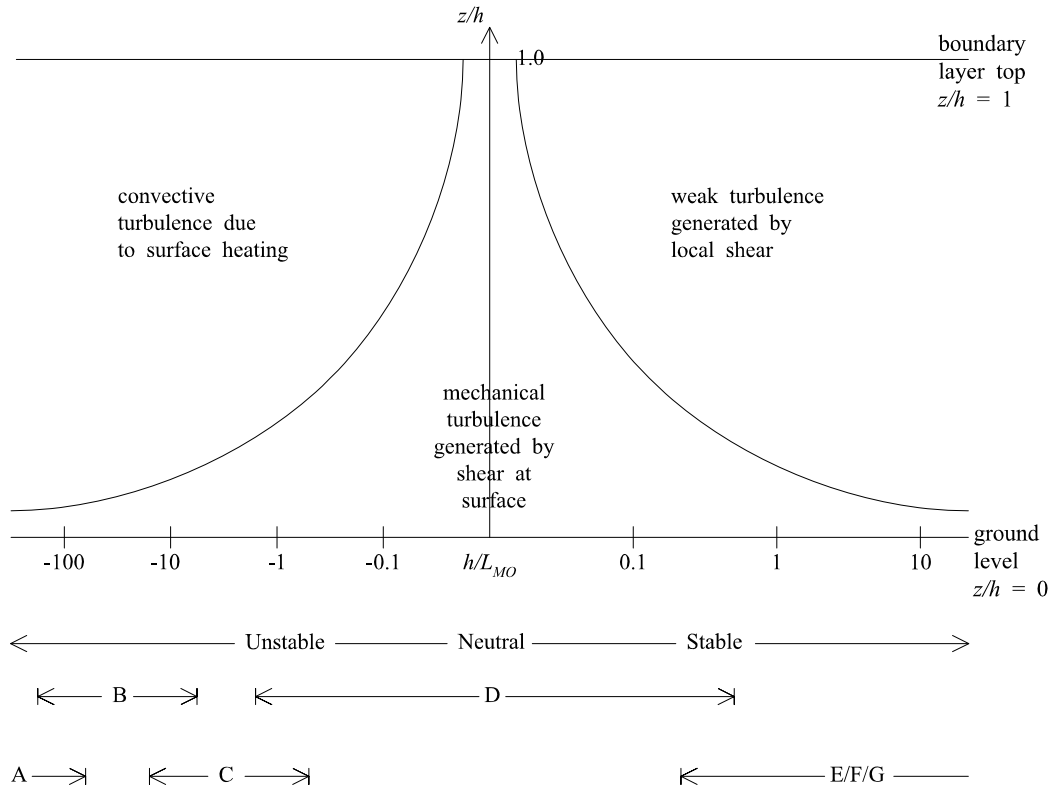


Figure 5.1 – Non-dimensional schematic representation of variation of Monin-Obukhov length with atmospheric stability.

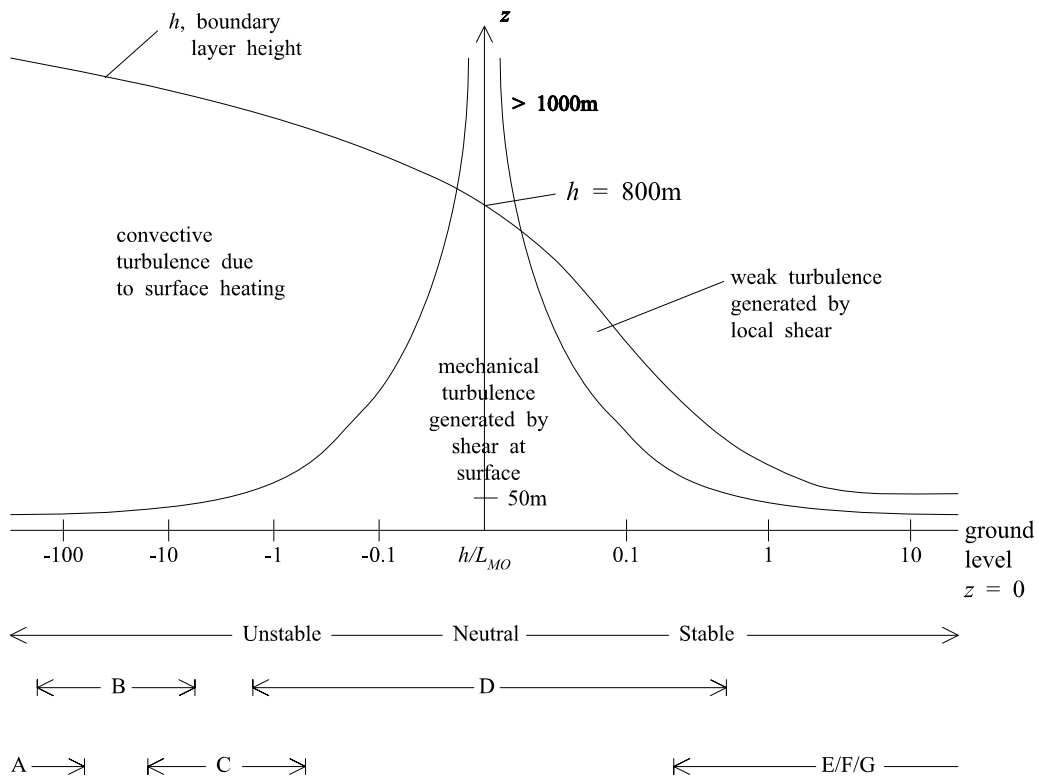


Figure 5.2 – Dimensional schematic representation of variation of Monin-Obukhov length with atmospheric stability.

5.2.1 Boundary layer structure

FLOWSTAR calculates boundary layer variables, listed in **Table 5.4**, at different heights. Vertical profiles are expressed as functions of z/L_{MO} and z/h and have been derived from experimental data (Caughey and Palmer (1979), van Ulden and Holtslag (1985), Hunt *et al.* (1988c)). These variables are used, in turn, by other modules.

$U(z), \frac{dU}{dz}, \frac{d^2U}{dz^2}$	Mean wind speed (m/s) and its first (/s) and second derivatives (/s ²)
$\sigma_u(z), \sigma_v(z), \sigma_w(z)$	Root mean square (r.m.s.) turbulent velocities (m/s)
$\Lambda_v(z), \Lambda_w(z)$	Turbulent length scales (m)
$\varepsilon(z)$	Energy dissipation rate (m ² /s ³)
$T_L(z)$	Lagrangian time scale (s)
$N(z)$	Buoyancy frequency (/s)
$T(z)$	Temperature (K)
$\rho(z)$	Density (kg/m ³)

Table 5.4 - Boundary layer variables calculated by FLOWSTAR.

5.3 Complex terrain module

The complex terrain module calculates a three-dimensional flow and turbulence field. There are two possible flow field solutions. The flow field solution used depends on the meteorological conditions. The critical parameter is the Froude number, Fr , which is defined using the maximum height of the terrain to be

$$Fr = \frac{U(h_{max})}{N(h_{max})(h_{max} - \bar{h})}, \quad (5.2)$$

where h_{max} is the height of the highest hill, \bar{h} is the mean height over the terrain, U is the flat terrain wind velocity value and N is the buoyancy frequency. The critical Froude number is 1.5.

The critical Froude number currently used by the ADMS 4 model is 1.0.

The terrain height is specified at up to 16500 points which are interpolated by the model onto a regular grid of up to 128×128 points. The best results are achieved if the points at which the elevation (and surface roughness, if it varies) is specified are spaced regularly.

Convective, Neutral and Moderately Stable Conditions ($Fr \geq 1.5$)

FLOWSTAR is derived from the theoretical work of Jackson and Hunt (1975) and Hunt et al (1988a, 1988b). The model is based on the premise that different processes dominate the flow dynamics in layers at different heights above the ground; thus in the inner layer shear stress perturbations are locally important and are described by a mixing length closure whilst the flow is also impacted upon by pressure gradients. These can be determined from the outer layer flow where stratification plays an important role but where shear stress perturbations have little influence. There is a transitional or middle layer between the inner and outer layer.

The airflow model uses linearised analytical solutions of the momentum and continuity equations. FLOWSTAR models the flow well typically for slopes up to 1 in 2 (upwind slopes and hill summits) and up to 1 in 3 locally in hill wakes. The model is also valid for larger slopes, though it may locally underestimate flow perturbations. Spatial scales treated by the model range from tens of metres up to several kilometres (the effects of roughness and terrain can be modelled separately). The airflow model has been extensively tested with laboratory and field data.

Very Stable Conditions ($Fr < 1.5$)

When very stable flows approach an isolated hill, the flow may divide, with the air above a certain height, h_c (the *dividing surface*) flowing over the hill in a “terrain-following” manner and the air below the dividing surface flowing around the hill in a 2-dimensional flow. This is shown in **Figure 5.7**. The height of the dividing surface is defined by an energy balance equation which locates the lowest height at which the kinetic energy of an air parcel in the flow approaching the hill is equal to the potential energy attained by elevating an equivalent fluid parcel from this height to the top of the hill:

$$\frac{1}{2}U^2(h_c) = \int_{h_c}^{h_{max}} N^2(z)(h_{max} - z) dz. \quad (5.3)$$

The flow below the dividing surface is two-dimensional potential flow apart from upstream flow in a thin layer close to the terrain. Above the dividing surface, the flow is terrain following with the exception of flows where the Froude number approaches 1.5 from below. In this parameter range, a weighted average of the $Fr \geq 1.5$ and terrain following flow fields is used.

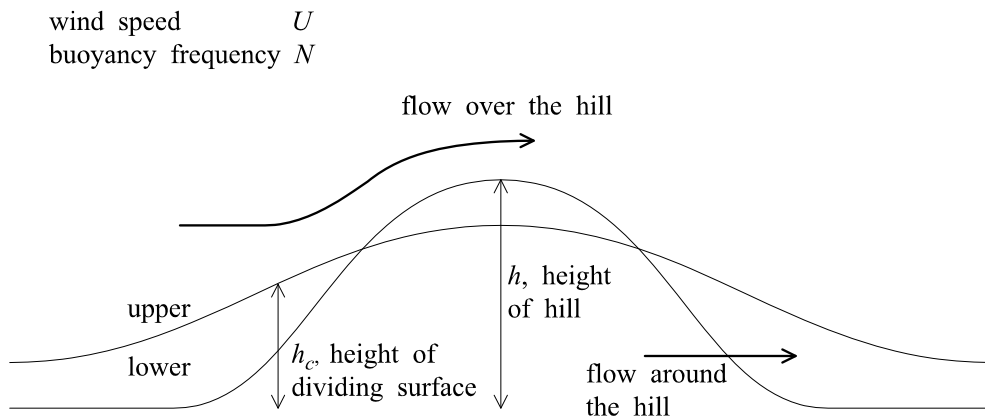


Figure 5.3 – Effect of a hill on the flow in very stable conditions.

Running the Complex Terrain Module

During a model run the following calculations take place:

- interpolation onto local grid of terrain and roughness data (if variable)
- calculation of mean airflow
- calculation of shear stress and turbulence

It is not recommended that the model be used unless hill slopes are greater than about 1 in 10 or there are large surface roughness changes.

The model can be used for very large changes in surface roughness. An order of magnitude variation in the surface roughness is allowable with the approximations made in the calculation.

5.4 Long term averages

This section describes the calculation of the wind and turbulence fields averaged over all the input met conditions.

Let us consider the long term wind field at a particular point. If we take (u_i, v_i, w_i) to be the wind vector at a particular point for met. condition i , with u_i , v_i and w_i being the wind components in the x-, y- and z- directions respectively, then

$$(U_{LT}, V_{LT}, W_{LT}) = \frac{1}{f_{total}} \sum_{i=1}^N f_i (u_i, v_i, w_i). \quad (5.4)$$

is the **mean wind vector**, where f_i is the frequency of occurrence of met. condition i , $f_{total} = \sum_{i=1}^N f_i$ is the total frequency of all the met. conditions and N is the number of hours represented by the valid met. lines. (Note that if the met. data are not statistical, all the frequencies f_i are equal to 1. Appendix A gives further information about the different types of met. data.)

The **mean horizontal wind speed** at a point is given by

$$\frac{1}{f_{total}} \sum_{i=1}^N f_i \sqrt{u_i^2 + v_i^2}. \quad (5.5)$$

In addition, the **magnitude of the mean horizontal wind vector** is calculated. This is given by

$$\sqrt{(U_{LT}^2 + V_{LT}^2)}. \quad (5.6)$$

The mean turbulence field is defined in a similar way to the mean flow field. That is if we take $(\sigma_{ui}, \sigma_{vi}, \sigma_{wi})$ to be the turbulence components in the x-, y- and z- directions respectively at a particular point for hour i , then the **mean turbulence field**, $(\Sigma_{uLT}, \Sigma_{vLT}, \Sigma_{wLT})$, is defined by

$$(\Sigma_{uLT}, \Sigma_{vLT}, \Sigma_{wLT}) = \frac{1}{f_{total}} \sum_{i=1}^N f_i (\sigma_{ui}, \sigma_{vi}, \sigma_{wi}). \quad (5.7)$$

APPENDIX A

Choosing Meteorological Data

There are essentially 4 different types of meteorological data that can be used with FLOWSTAR. These are:

- (a) Data from (or edited from) an example file supplied in the `<install_path>\data` directory
- (b) Data files created by the user from their own available data e.g. from a met. station on site
- (c) Hourly sequential data obtained from a supplier
- (d) Statistical data obtained from a supplier, e.g. the UK Met. Office

(Please refer to Appendix C for contact details of met. data suppliers.)

(a) Data entered from a prepared example file

There are a number of example met. files provided with FLOWSTAR. The example files are installed in the `<install_path>\data` directory of your computer. A particularly useful file is *R91a-g.met*, which contains seven lines of met. data that correspond *approximately* to stability classes A-G. This file can be viewed in an editor such as Notepad or WordPad and is shown below in **Figure A-1**.

```
*****
This file sets up the equivalent of R91 Categories A to G
boundary layers. As in R91:
A: U(10) = 1 m/s and H = 1300 m
B:           2           900
C:           5           850
D:           5           800
E:           3           400
F:           2           100
G:           1           100
*****

VARIABLES :
4
U
FTHETA0
PHI
H

DATA :
1.0, 113.0, 270.0, 1300.0
2.0,  84.0, 270.0,  900.0
5.0,  74.0, 270.0,  850.0
5.0,   0.0, 270.0,  800.0
3.0, -10.0, 270.0,  400.0
2.0,  -6.0, 270.0,  100.0
1.0,  -0.6, 270.0,  100.0
```

Figure A-1 – The met. file *R91a-g.met*.

This file can be used as it is, or edited for instance by changing the wind direction (PHI) to investigate the effect of different wind directions on the flow-field over complex terrain. For a list of the variable names and their meanings, refer to Section 5.1 of this User Guide.

Other files in this directory can be opened and edited in the same way. A useful file to look at is called *metdemo.met*, which explains the format required when preparing your own met. files.

(b) Data files created by the user

It is possible for users of the model to create their own met. files, but due care must be taken that at least the minimum met. parameters are specified and that the files are saved as comma separated files with the *.met* extension. This may be appropriate if the site has a met. station of its own or if data have been measured during field monitoring campaigns.

The minimum data required are wind speed U, wind direction PHI and either:

- the Julian Day Number, TDAY
- time of day, THOUR
- cloud cover, CL

or

- sensible surface heat flux, FTHETA0

or

- reciprocal of Monin-Obukhov length, RECIPLMO.

Additional met. parameters can be added to the met. files, and should be included if accurate values are known. In other cases it is better to allow the model met. data processor to calculate parameter values rather than to make inaccurate estimates.

(c) Hourly sequential data obtained from a supplier

Hourly sequential data are normally available for periods of one year. Each line of data represents one hour of measurements, and therefore a data file for one year contains 8760 lines of data. It is the type of data used calculating the flow field averaged over a long period. An example of the beginning of an hourly sequential file is shown in **Figure A-2**. Wind direction measurements (PHI) are reported to the nearest 10 degrees, i.e. the wind data are in 10 degree sectors.

```

VARIABLES:
9
STATION DCNN
YEAR
TDAY
THOUR
T0C
U
PHI
P
CL
DATA:
8009.0,1996.0, 1.0, 0.0, 5.0, 10.8, 160.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 1.0, 5.1, 11.3, 150.0, 0.0, 3.0,
8009.0,1996.0, 1.0, 2.0, 5.3, 11.3, 160.0, 0.0, 1.0,
8009.0,1996.0, 1.0, 3.0, 5.6, 9.8, 160.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 4.0, 5.5, 8.2, 150.0, 0.0, 8.0,
8009.0,1996.0, 1.0, 5.0, 5.5, 8.2, 150.0, 0.0, 2.0,
8009.0,1996.0, 1.0, 6.0, 6.0, 9.3, 150.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 7.0, 6.1, 7.7, 150.0, 0.0, 8.0,
8009.0,1996.0, 1.0, 8.0, 6.1, 8.2, 140.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 9.0, 6.1, 9.8, 150.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 10.0, 6.8, 11.3, 160.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 11.0, 7.3, 11.3, 160.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 12.0, 7.7, 10.3, 160.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 13.0, 7.5, 10.3, 160.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 14.0, 7.4, 10.8, 160.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 15.0, 7.3, 10.3, 160.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 16.0, 6.9, 7.7, 150.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 17.0, 6.8, 6.7, 150.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 18.0, 6.0, 6.7, 150.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 19.0, 6.0, 7.7, 150.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 20.0, 5.4, 6.2, 150.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 21.0, 4.5, 6.2, 140.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 22.0, 4.1, 6.7, 130.0, 0.0, 7.0,
8009.0,1996.0, 1.0, 23.0, 4.4, 6.7, 150.0, 0.0, 7.0,

```

Figure A-2 – Example of hourly sequential met. data file.

Since sequential data files consist of continuous hour-by-hour measurements, they are a better representation of actual met. conditions than statistically analysed data files (see below). However, it is important to note that year to year variations occur in met. conditions.

Up to five years' worth of data may be included in a sequential data file.

(d) Statistical data obtained from a supplier

Statistical data files normally include met. data for a period of ten years. The aim of using statistically analysed data is to take account of the variation in met. conditions from year to year. Each hourly measurement for that period is recorded and put into a bin or class representing a range of different values for different met. parameters. For example, in the file represented in **Figure A-3**, the data were categorized into five classes of wind speed (U), twelve classes of wind direction (PHI) (i.e. a wind sector size of 30 degrees), seven classes of surface sensible heat flux (FTHETA0), seven classes of boundary layer height (H), and three classes of precipitation (P).

There are over 2000 lines of data in a statistical met. file, each line corresponding to a particular combination of met. conditions that occurred, for example the first line of met. data corresponds to the first class or bin of each of the five parameters. Each line of met. data has an associated frequency representing the number of hours that occurred during the period of the data (usually ten years) with met. conditions within the ranges described by that line of data. Statistical files can be viewed in an editor, and an example showing the beginning of a statistical file is given in **Figure A-3**.

```
FREQUENCY ANALYSIS OF METEOROLOGICAL DATA MEASURED AT
*****

Station latitude           :*** deg  ** min north.
Station longitude         :*** deg  ** min west.
Station height above mean sea level : 68 metres.
Effective height of anemometer above ground level: 10 metres.
Roughness length assumed at station :0.20 metres.

Period of analysis:      **/**/**** to **/**/****.

The parameters analysed are as follows:
  Parameter and units           No. of classes
  Hourly average wind speed (m/s) (=U)           5
  Hourly average wind direction (degrees true) (=PHI) 12
  Surface sensible heat flux (W/m**2) (=FTHETA0) 7
  Boundary layer depth (m) (=H)                 7
  Hourly precipitation amount (mm) (=P)         3
The wind direction is the direction from which the wind is blowing, measured clockwise from north. The surface sensible heat flux and boundary layer depth are not measured but estimated from measured quantities.
Hourly precipitation amount includes contributions from water falling as snow, hail etc.
```

Figure A-3 – Example of statistical met. data file.

*Users should ensure they read the information at the beginning of a statistical met. file as it provides information about the **Effective height of anemometer above ground**. For the majority of files it is 10 m but occasionally it is at some other height and the correct value should be entered into the **Meteorology** screen.*

Statistical data has a number of advantages over sequential data.

- There are about 2000 lines of data to process in FLOWSTAR with a statistical met. file rather than 8760 in a one year sequential met. file; run times are therefore significantly shorter for statistical than sequential data.
- Statistical data is representative of the met. conditions which occurred over several years (usually ten); year-to-year variations in conditions are therefore accounted for. This is not true for sequential data.

A disadvantage of using statistical met. data is that because the data are categorised into bins with pre-defined upper and lower bounds, it is the mean for each bin rather than the actual hourly value of a parameter that is processed by FLOWSTAR. Thus extreme conditions are smoothed out. For example, there may be a few hours in a particular year (e.g. 1995) when the surface heat flux is extremely high thus generating a lot of convective mixing. Using sequential data, the data file would contain the actual high surface heat flux value for that particular hour, thus representing actual conditions. Using statistical data, the value of surface heat flux used would be the mean value of the appropriate class. In this case, this mean value would be less than the true hourly value and would thus underestimate the amount of convective turbulence.

APPENDIX B

Viewing Terrain Data and Creating Files from OS Digital Data

FLOWSTAR includes a utility to convert digital terrain data into FLOWSTAR input format. This is called the ‘Terrain Converter’. The types of digital terrain data supported by this utility are listed below:

1. Ordnance Survey (GB) Landform PANORAMA NTF
2. Ordnance Survey (GB) Landform PROFILE NTF
3. IGN XYZ (FR)

A separate utility exists for OS Northern Ireland terrain data; this is available to download from the User Area on the CERC website (www.cerc.co.uk/users.htm). Instructions for converting data from other different formats are given in Helpdesk Note No. 49 ‘Setting up terrain data for ADMS & FLOWSTAR’, also available to download from the User Area.

This appendix will guide the user through the process of using the Terrain Converter to create a FLOWSTAR terrain file.

Identifying Terrain Data Required

When using OS (GB) terrain data, the Terrain Converter can identify the tiles that you need to purchase from the terrain area that you request.

Step 1 Identify the UK National Grid source coordinates for the problem.

Click on Utilities, Terrain Converter... from the menu bar at the top of the main FLOWSTAR interface. This will open the screen shown in **Figure B-1**.

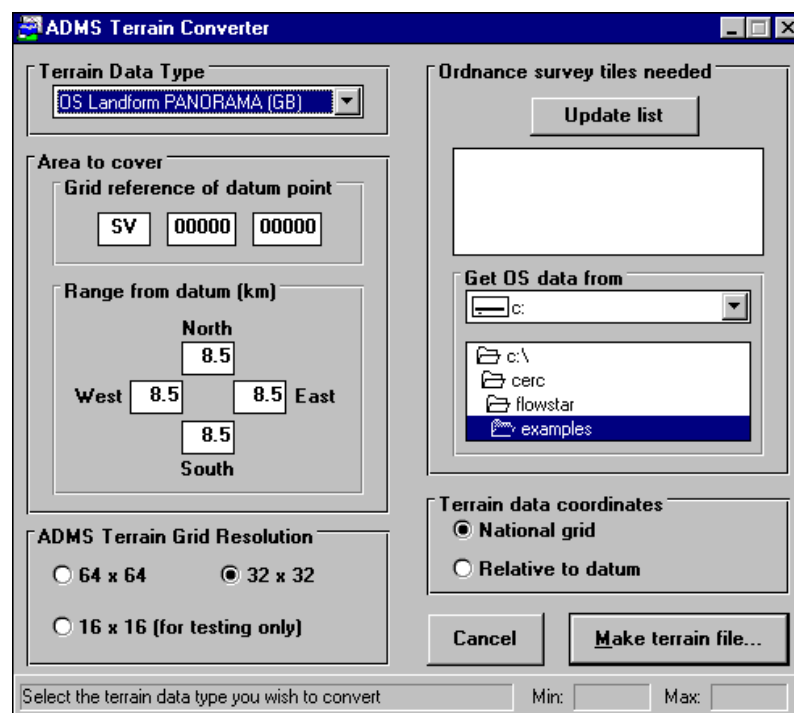


Figure B-1 – Main screen for Terrain Converter utility.

- Step 2** Use the drop-down list box to select either OS Landform PANORAMA (GB) or OS Landform PROFILE (GB) (this example uses OS Landform PANORAMA data)
- Step 3** Double-click on the 2-lettered cell shown as **SV** here to open the map of the National Grid as shown in **Figure B-2**.

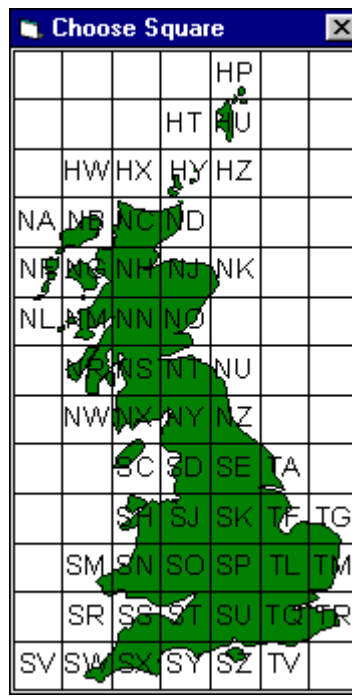


Figure B-2 – Reference map of UK showing National Grid 100 km squares.

Each 2-lettered square is 100km×100km. It is made up of 25 smaller squares each with an area of 20km×20km. The coordinate (0,0) is the bottom left-hand corner of the square SV.

The user can create the terrain file with points Relative to datum or in National Grid coordinates. This means that the coordinates can either be at and around (0,0) or they can be given in 6 figure National Grid coordinates (6 figure easting, 6 figure northing).

In this appendix National Grid coordinates are used.

Referring to **Figure B-3**, if the site of interest is at the point marked by a star it may be referenced either as SD 63000, 42000 or as 363000, 442000. That is, you would move 3 squares to the east of the (0,0) coordinate and 4 squares to the north of the (0,0) coordinate to locate the bottom left corner of the tile SD. The five and six figure numbers are both in metres, the first format referenced to the lower left corner of the grid square and the second referenced to the lower left of the whole UK map.

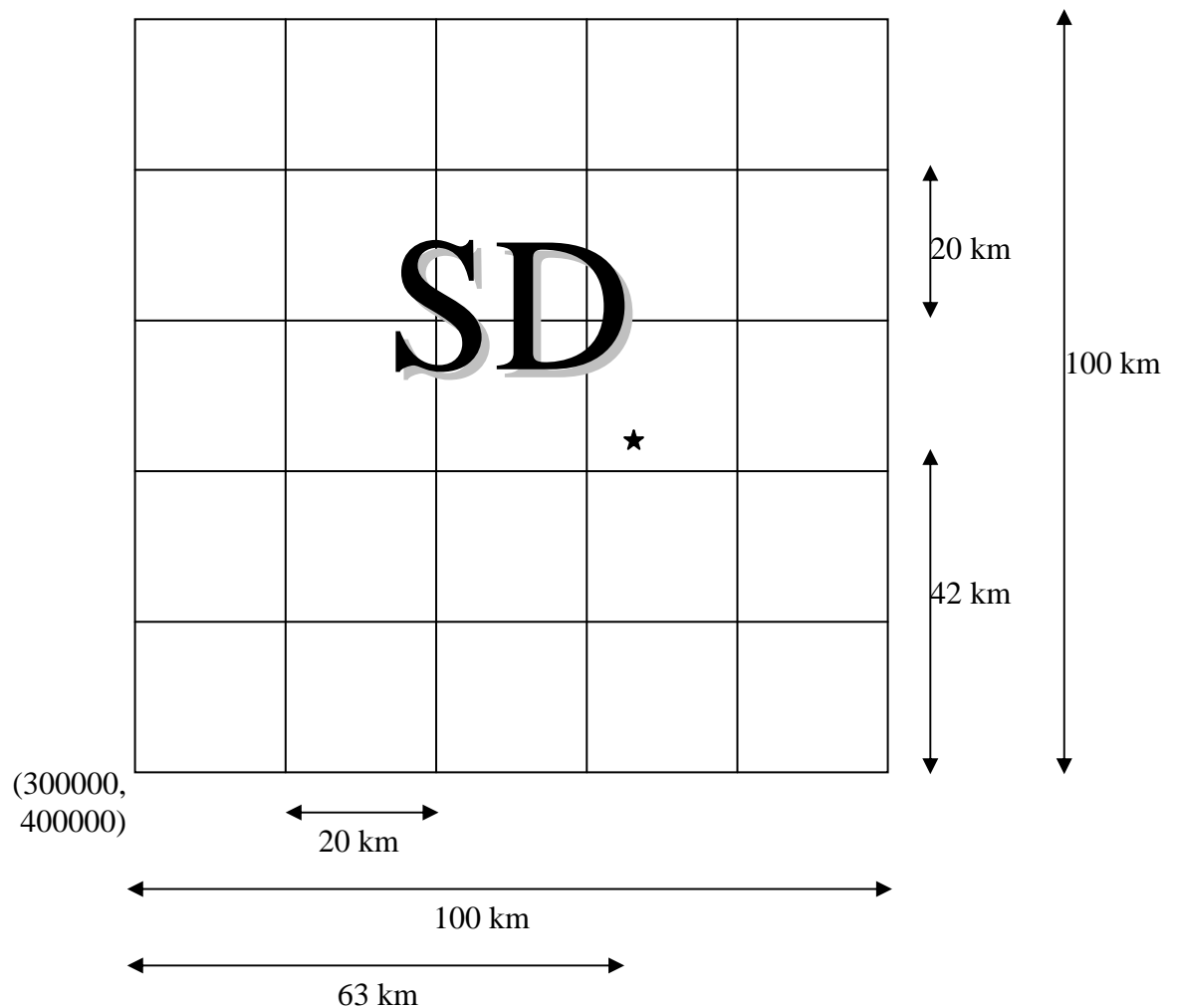


Figure B-3 – Example of use of National Grid coordinates of a point, marked by a star.

Each Ordnance Survey Landform PANORAMA tile is given a name based on the two-letter five-figure system. In **Figure B-3**, the lower left corner of the tile containing the star is given by SD 60000, 40000, so that the tile is called SD64.

Landform PROFILE tiles cover a smaller area, 5kmx5km. These tiles are named using a similar convention to the Landform PANORAMA tiles, but with 2 extra characters to identify which quadrant of the larger tile it lies in. For example, the Landform PROFILE tile with the lower left corner at SD 60000, 40000 is called SD64sw to indicate that it is in the south-west quadrant of SD64.

Step 4 Double-click on the square SD to enter it into the cell. In this example enter the source location as **SD 70000, 50000**. This is in the centre of the tile.

Step 5 In the Range from Datum (km) cells type in 10 km in each direction and click on the Update list button. This will reveal that only one tile is required i.e. SD 64. This is shown in **Figure B-4**. This area would require the *whole* of SD64 to be used in the terrain file. If you only chose, say, 5 km in each direction you would still be required to purchase the same tile but the terrain file created would only use a portion of the available data.

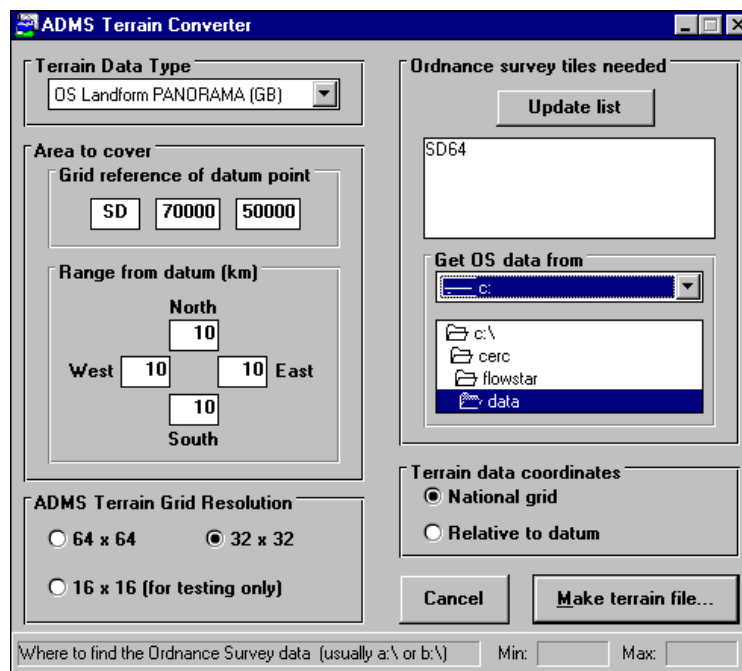


Figure B-4 – Example of the calculation of OS tiles required for given area to cover (datum and range from datum).

Now change one of the Range from datum (km) values to 11 km and click on Update list again. You will now see that more tiles are required. This lets you know which tiles you need to purchase.

Purchasing UK OS Digital Terrain Data

OS digital terrain data for the UK may be obtained either directly from Ordnance Survey, or from a number of other suppliers: contact details are given in Appendix C.

The type of data required is either **Landform Profile** data (supplied in 5kmx5km tiles) or **Landform Panorama** data (supplied in 20kmx20km tiles). Landform Panorama data has been discontinued by Ordnance Survey, but is still available to purchase from other suppliers.

When purchasing either format of Landform data, be careful to make sure that you request **NTF** format (not DXF) and **DTM** data (not Contours).

Converting Digital Data into Terrain Files for use in FLOWSTAR Calculations
OS (GB) Landform PANORAMA and Landform PROFILE data

Step 1 With the screen in **Figure B-4** in view choose a grid size of 32×32 as the optimum to balance accuracy and speed. In the Get OS data from box, browse to locate the CD drive or directory where the data are stored.

If more than one tile is required to make the terrain file, all tiles must be saved in the same directory.

Step 2 Click on Make terrain file.... This will open the screen shown in **Figure B-5**. Choose where you want to save the file together with the file name with extension *.ter*.

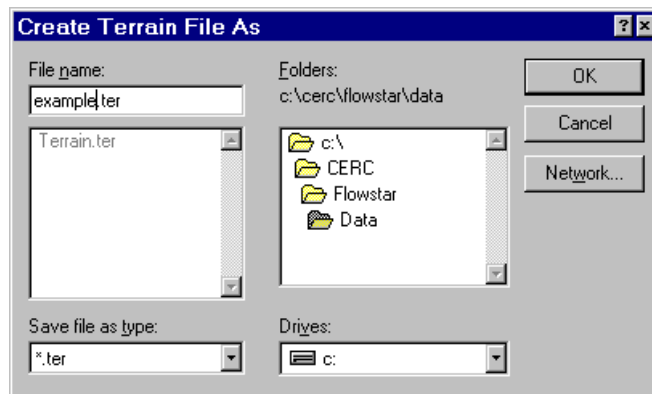


Figure B-5 – Naming the terrain file to be created.

Click on OK. This will open the screen shown in **Figure B-6**.

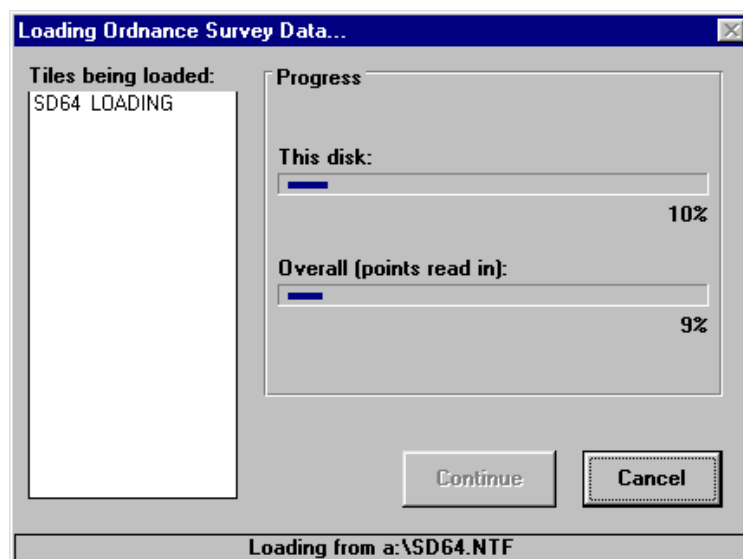


Figure B-6 – Screen displayed while OS data is being loaded from tiles.

- Step 3** Click on Continue to create the file. Tiles still required will have Wanted written next to them. When the ADMS terrain file has been successfully created, the Terrain Converter will beep, and show the following message:



IGN XYZ (France) Input data

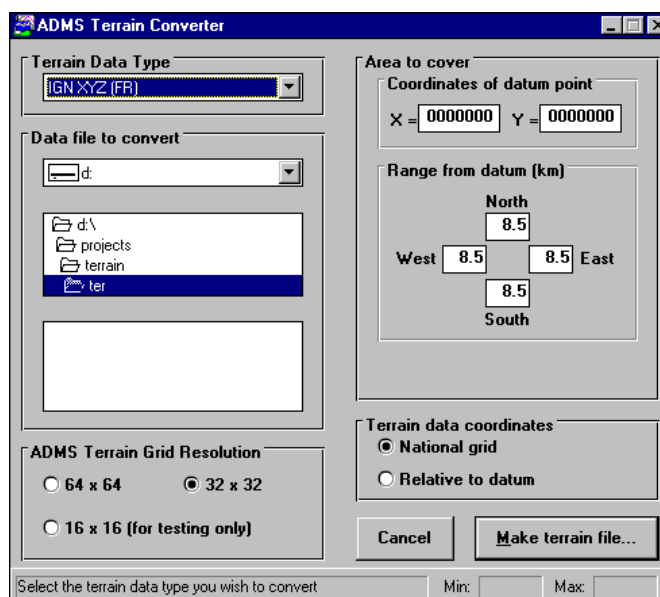
When choosing the area that you wish to cover with FLOWSTAR terrain data, you must think about the boundaries of your IGN data.

If the area you wish to cover overlaps a coastline, and therefore contains missing data over the sea, then proceed as normal. The Terrain Converter will prompt you to identify the missing data as sea, and will then set the elevation of missing data points to be zero.

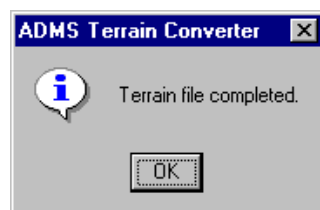
If this is not the case, then the area you choose to cover should lie within the area covered by your IGN data. The Terrain Converter will detect any missing data, and will prompt you to either re-select your area manually, or to use the Terrain Converter facility to re-calculate the extent of the area to cover to avoid missing data at the edges.

To convert French IGN XYZ data to FLOWSTAR terrain data, follow these simple steps:

- Step 1** Select IGN XYZ (FR) from the drop-down list in the top, left corner of the Terrain Converter interface.

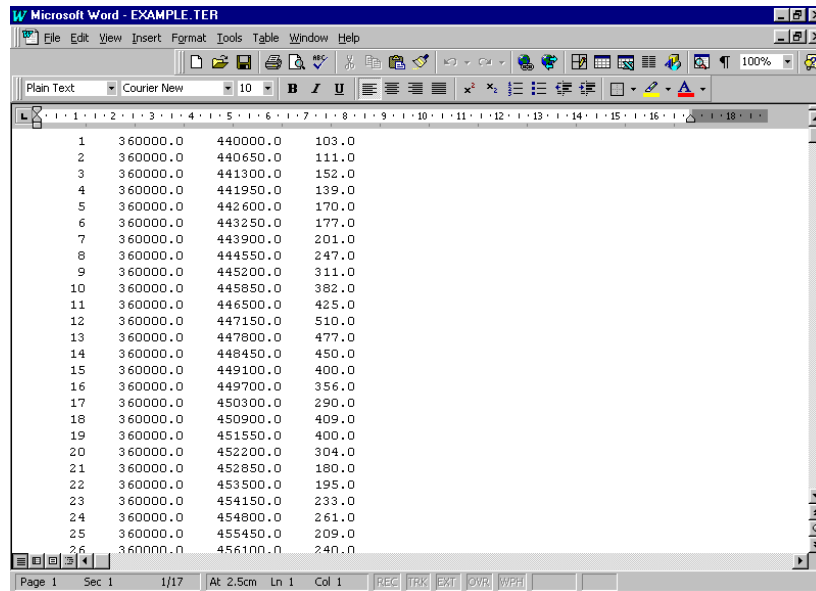


- Step 2** In Data File to convert, select the drive, directory and file name of the IGN terrain file that you wish to convert to FLOWSTAR format.
- Step 3** Select the ADMS Terrain Grid Resolution you require. A 32x32 output terrain grid is recommended for most situations, unless the terrain variability is very great, in which case 64x64 would be suitable.
- Step 4** In Area to cover, enter the coordinates of the datum point, in metres. This may be any point, and does not have to lie in the centre of the required area. However, this point should be in the centre of the area of interest, i.e. the location of the primary source, or the centre of the output grid.
- Step 5** Also in Area to cover, enter the range from the datum point (in kilometres) that you wish the FLOWSTAR terrain grid to cover.
- Step 6** Finally, select the Terrain Data coordinates. If you choose National Grid then the coordinates in the FLOWSTAR Terrain file will be the same as the coordinate system as the IGN terrain data. If you choose Relative to Datum then the coordinate system used in the FLOWSTAR terrain file will have the origin at the datum point.
- Step 7** You are now ready to make the FLOWSTAR terrain file. Click on the Make the terrain file... button.
- Step 8** Specify a directory and file name for the newly created FLOWSTAR terrain file.
- Step 9** When the FLOWSTAR terrain file has been successfully created, the Terrain Converter will beep, and show the following message:



Viewing the contents of a FLOWSTAR terrain file

- Step 1** Open the terrain file in an editor such as Notepad or WordPad or in a spreadsheet program such as Excel. You will see that there are 4 columns of data, as in **Figure B-7**. The first column is a counter.



The screenshot shows a Microsoft Word window titled 'EXAMPLE.TER'. The document contains a table with 4 columns and 26 rows. The first column is a counter from 1 to 26. The second column contains the value '360000.0' for all rows. The third column contains values ranging from 440000.0 to 456100.0 in increments of 100.0. The fourth column contains values ranging from 103.0 to 240.0 in increments of 10.0.

1	360000.0	440000.0	103.0
2	360000.0	440650.0	111.0
3	360000.0	441300.0	152.0
4	360000.0	441950.0	139.0
5	360000.0	442600.0	170.0
6	360000.0	443250.0	177.0
7	360000.0	443900.0	201.0
8	360000.0	444550.0	247.0
9	360000.0	445200.0	311.0
10	360000.0	445850.0	382.0
11	360000.0	446500.0	425.0
12	360000.0	447150.0	510.0
13	360000.0	447800.0	477.0
14	360000.0	448450.0	450.0
15	360000.0	449100.0	400.0
16	360000.0	449700.0	356.0
17	360000.0	450300.0	290.0
18	360000.0	450900.0	409.0
19	360000.0	451550.0	400.0
20	360000.0	452200.0	304.0
21	360000.0	452850.0	180.0
22	360000.0	453500.0	195.0
23	360000.0	454150.0	233.0
24	360000.0	454800.0	261.0
25	360000.0	455450.0	209.0
26	360000.0	456100.0	240.0

Figure B-7 – Example of a terrain file (*example.ter*).

- Step 2** Now open Surfer. Open a new plot window, click on Grid, Data... and browse for the terrain file you have created, ensuring that the Files of type menu is set to 'All Files (*.*)'. Click on Open. Select the delimiter as Comma in the next screen, **Figure B-8**.

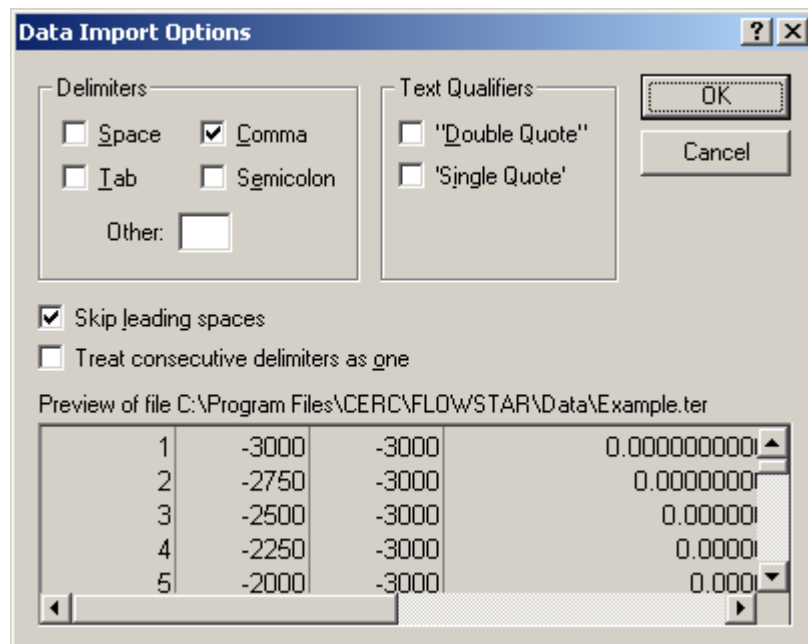


Figure B-8 – Importing a terrain file into Surfer.

Step 3 From **Step 1**, we saw that the first column in the terrain file contained a counter, so in the screen shown in **Figure B-9** we select columns B, C and D to be the X, Y and Z data for the contour plot. Click on OK.

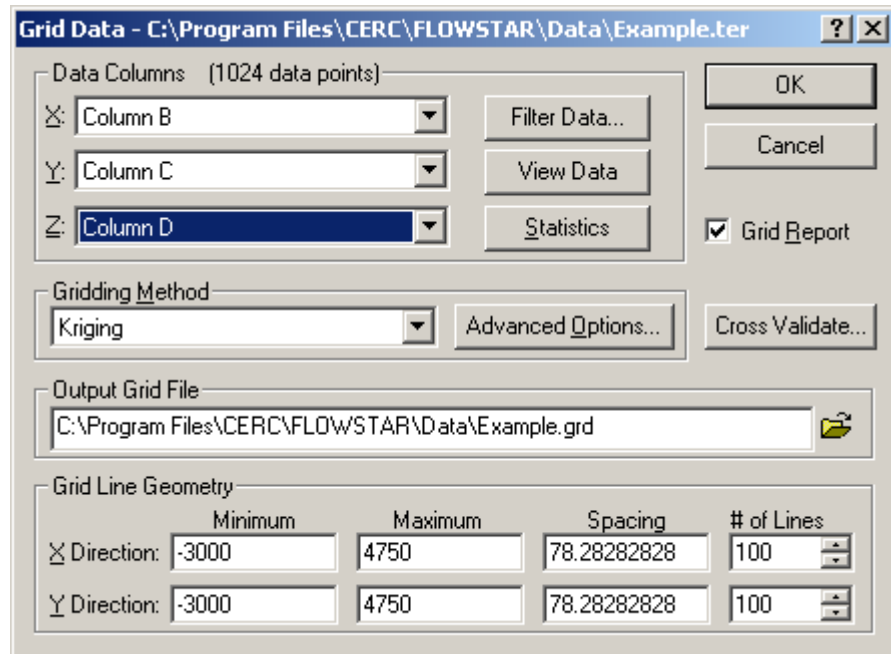


Figure B-9 – Settings for gridding a terrain file in Surfer.

Step 4 The terrain file is gridded in Surfer. Now go to Map, Contour Map, New Contour Map... and select the file *example.grd* that Surfer has just created using your terrain file. Click on OK both here and in the next screen to see a 2-dimensional contour plot of your area of terrain as shown in **Figure B-10**.

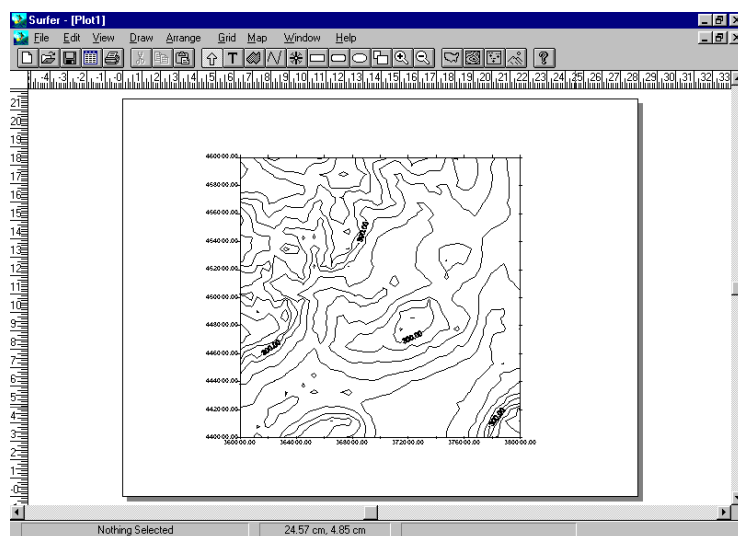


Figure B-10 – Contour plot of terrain file produced in Surfer.

- Step 5** To edit the contour levels plotted in a Surfer plot to provide more detail, double-click on the contours. In the Levels tab, click on the Level column header button to bring up the screen shown in **Figure B-11**.

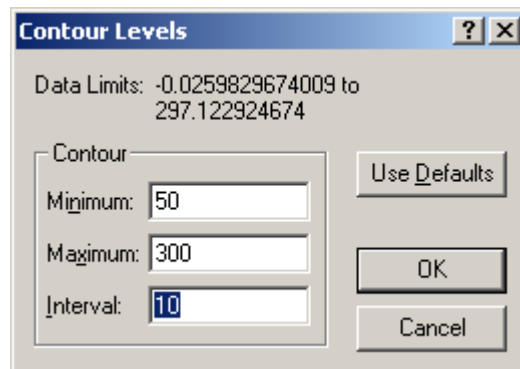


Figure B-11 – Setting contour levels in Surfer.

Change the interval to a smaller number to get more detailed contours on the plot and click OK. This may change your colour scheme to black/grey. To change it to something else click on the Fill column header button to bring up the screen shown in **Figure B-12**.

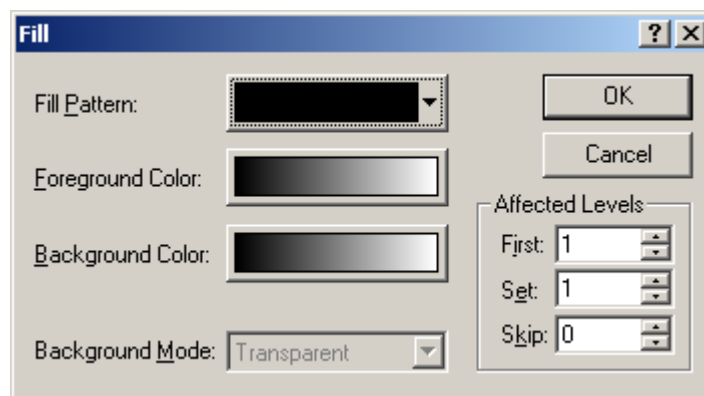


Figure B-12 – Setting the spectrum of colours and patterns for the contour plot.

Click on the Foreground Colour box to bring up the screen shown in **Figure B-13**.

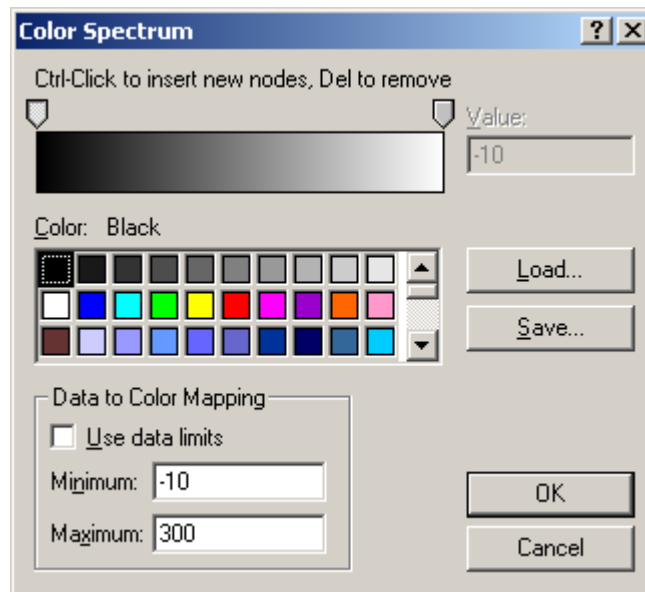


Figure B-13 – Choosing colours for filling contours in Surfer.

Click on the left arrow above the colour bar and choose the colour you require for the minimum, e.g. light brown is a good choice. Click on the right arrow and then choose a colour for the maximum, say dark brown.

Click on OK twice to return to the screen shown in **Figure B-14**.

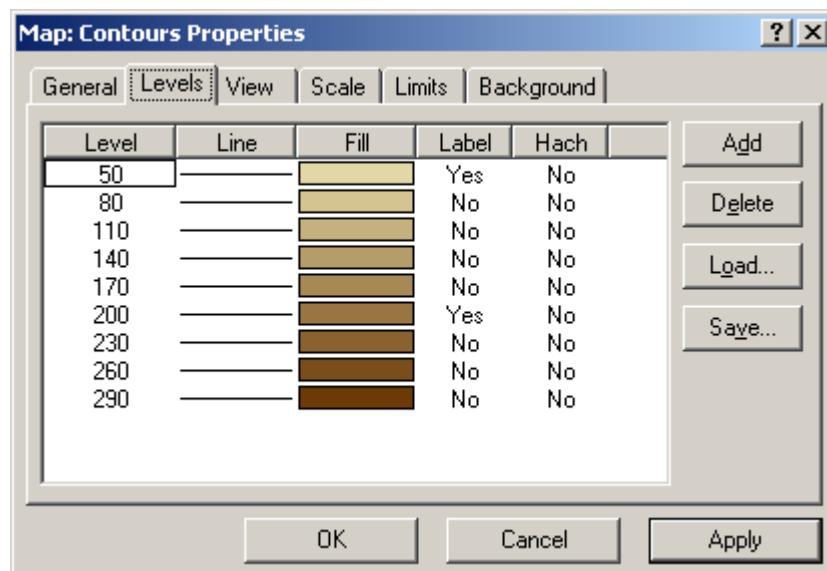


Figure B-14 – Main screen for refining details of Surfer contour plots.

Select the General tab and ensure that the Fill Contours box is ticked. Click on OK again to return to the coloured contour plot. Look at the coordinates of this contour plot to check that the area you require is covered.

Step 6 Save the 2D plot as *example.srf* ready to open later. Once you are happy with the colours and levels of the 2D plot, you can create a 3D view of the same area of terrain.

The appearance of the final 3D surface plot, in terms of contour levels, colours, etc. must first be set up in the 2D plot.

To do this go to Map, Wireframe... and select the correct *.grd* file, e.g. *example.grd*. Click OK on the next screen and a 3D plot will be created over the 2D plot.

Click on Edit, Select All (or click on F2) and then on Map, Overlay Maps to create the 3D view as shown in **Figure B-15**.

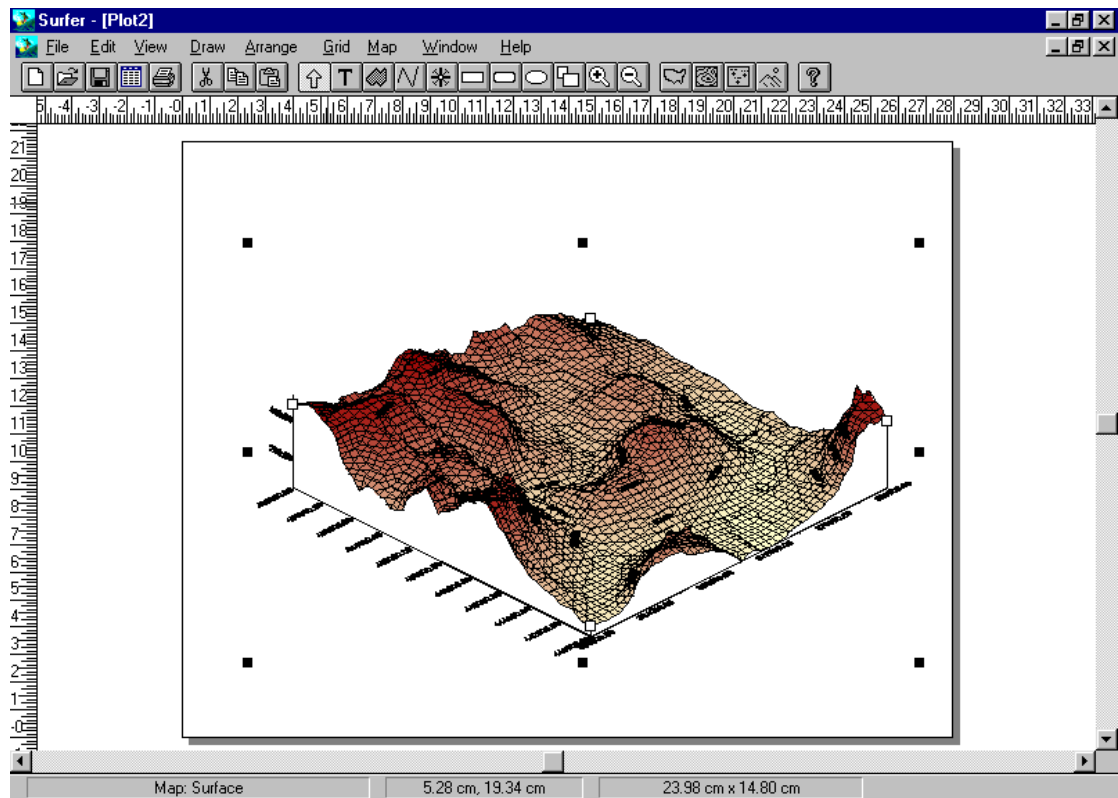


Figure B-15 – 3-D visualisation of terrain contour plot.

Step 7 Click on Map, Trackball to experiment with the angle and rotation of the view. Save the plot as *examp3d.srf*

APPENDIX C

Sources of Help and Contact Information

FLOWSTAR Helpdesk

Tel: (01223) 357773 – ask for FLOWSTAR Helpdesk

Fax: (01223) 357492 – marking your fax “FAO FLOWSTAR Helpdesk”

Email: flowstar.help@cerc.co.uk

Web site: www.cerc.co.uk

This service is available to those with valid maintenance between the hours of 9.30am - 5.00pm (GMT in winter, BST in summer), Monday - Friday (excluding public holiday periods and 27-31 December).

Support contract

A valid support contract entitles the user to

- use of the FLOWSTAR Helpdesk,
- model upgrades,
- access to further technical advice and downloads on the User Area of the CERC website www.cerc.co.uk/users.htm,

All annual licence holders are entitled to free support. Permanent licence holders receive free support for one year, after which an annual support contract should be purchased.

Scope of the FLOWSTAR Helpdesk service

The scope of the Helpdesk Service is to provide answers to specific questions about using FLOWSTAR; to respond to any reported error messages that occur while running the model; and to record and report on any problems found. Where appropriate, CERC staff can also provide advice on setting up particular modelling scenarios and advice on interpreting the results.

Surfer problems should be directed to Golden Software, whenever possible.

Contact details for other organisations

1. For meteorological data files for the UK (ask for 'ADMS format'):

UK Met Office, Environmental Consultancy Group
FitzRoy Road
Exeter
Devon
EX1 3PB
United Kingdom

Tel: 0870 900 0100

Email: enquiries@metoffice.gov.uk

Fax: 0870 900 5050

Web: <http://www.metoffice.gov.uk/services/industry/data/general>

2. For both UK map tiles and terrain data (Landform PROFILE only):

Data supply team
Ordnance Survey
Romsey Road
Southampton
SO16 4GU

Tel: +44 (0)8456 05 05 05

Email: customerservices@ordnancesurvey.co.uk

Fax: +44 (0)2380 792 615

Web: www.ordnancesurvey.co.uk

3. For both UK map tiles and terrain data (Landform PANORAMA and Landform PROFILE)

eMapSite.com Limited
MASDAR House
No. 1 Reading Road
Eversley
Hants
RG27 0RP

Tel: 0118 973 6883

Email: sales@emapsite.com

Fax: 0118 973 0002

Web: www.emapsite.com

4. For queries on Surfer:

Golden Software, Inc.
809 14th Street
Golden,
CO 80401-1866 U.S.A.

Tel: +1 (303) 279-1021

Email: info@goldensoftware.com

Fax: +1 (303) 279-0909

Web: www.goldensoftware.com

APPENDIX D

References

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