Flowtube: A Groundwater Calculator for Salinity Estimation

R. M. Argent[a], **R. J. George**[b] **and W. Dawes**[c]

[a] *Centre for Environmental Applied Hydrology and Cooperative Research Centre for Catchment Hydrology, Department of Civil and Environmental Engineering, The University of Melbourne, 3010, Australia.*
(R.Argent@unimelb.edu.au)
[b]*Catchment Hydrology Group, Department of Agriculture, Bunbury, Western Australia*
[c]*CSIRO Land and Water, Canberra*

Abstract: Dryland salinity is now recognized as one of Australia's critical environmental problems. Over 25,000 km^2 of farmland are salt affected in Australia, primarily in Western Australia, and the area is increasing. Dryland salinity is being tackled in Western Australia through a rapid appraisal approach that will be applied to over 600 catchments over the coming years. The approach aims to analyze a range of farm management options to reduce the onset and extent of salinity. This requires a robust, technically sound, flexible, and user-friendly simulation program that captures the essential features of groundwater recharge and discharge processes. A program, named Flowtube, has been developed for this task. Flowtube allows users to specify details of a longitudinal catchment section, bounded by flowlines, and made up of connected cells that are flat-bottomed and straight-sided. Recharge values, representing management effects, are applied to flowtube cells, and the resulting groundwater level is estimated. The Flowtube groundwater model assumes flow occurs through a conducting aquifer, overlain by a semi-confining layer within which lies the groundwater surface. Calculation is based on mass continuity, with flux estimation via Darcy's equation, and solution is undertaken using an explicit scheme that steps from one cross-section to the next down the tube. One of the keys of Flowtube's success is the process by which user needs were identified and integrated in the application. This paper details the structure and use of the program, and the scientific basis underlying the program algorithms. Further development of Flowtube is being undertaken in a national project over 2001-2003 to expand its application to salt affected areas across all of Australia.

Keywords: Salinity; Groundwater modelling; Scenario analysis; Catchment management

1. INTRODUCTION

Dryland salinity has ruined, or is threatening, substantial areas of Australian agricultural land. Agricultural practices undertaken over decades have altered the hydrological balance by removing or reducing deep-rooted natural vegetation, and replacing these with plants that use less of the available water. Consequential rising water tables have remobilised salt and brought it to the soil surface.

Around the country, Governments are recognising that changes to agricultural practices, which result in reductions in groundwater accessions, should be considered for adoption. In Western Australian, for example, state policy [Government of Western Australia, 2000] covers a range of approaches to the management of salinity, including changing agricultural practices, adopting farm forestry, different productive uses of saline lands, and groundwater management. Before farmers can seriously consider these practices, information on the likely affects of alternative practices must be made available. One step in this direction is the AgET (formerly WAttle) model [Argent and George, 1997], a one-dimensional water balance calculator, which has been used for analysis of cropping and planting options for the past 5 years. Recently, the Department of Agriculture, Western Australia identified a need for a user-friendly tool that could be used to analyse the affects of changing groundwater accessions on local water tables. This paper reports on a groundwater calculator program, named "Flowtube", that was developed to meet this need.

The program is freely available, and program files, and technical and user manuals, can be downloaded from:

http://www.civag.unimelb.edu.au/~argent/flowtube/

2. PROGRAM OVERVIEW

The model underlying the Flowtube program was originally, and continues to be, developed as part of the Funnel model [Dawes et al. 1997].

The model is based on a finite difference solution to the one-dimensional Darcy's Law for saturated flow in a semi-confined aquifer. The conducting aquifer is assumed to be underlain by a non-leaking bottom (i.e. zero vertical flux boundary condition), overlain by an upper layer, and the groundwater surface is assumed to lie within the upper layer (i.e. the conducting aquifer is full).

The finite difference solution allows different aquifer properties, such as section width, and surface, groundwater and bottom elevation to be set at each of a series of cross sections along a tube of flow (Figure 1). These values, along with default program parameters, such as porosity and saturated hydraulic conductivity, are stored in case study or site-based files.

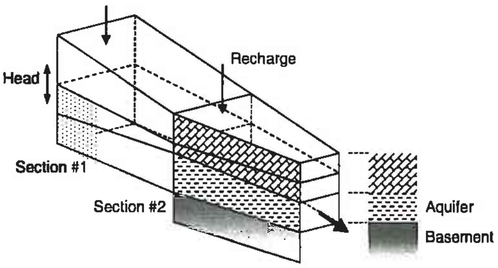


Figure 1. Flowtube conceptual construction.

Flow equation solution requires the imposition of initial and boundary conditions. These are:

- Initial values of groundwater piezometer head, at each section along the tube. Bore monitoring data are normally used for this.
- A no-flux boundary at the top of the flow tube, with a local piezometric head that has zero slope and is steady over time.
- An outlet boundary condition where ground water intersects the soil surface or where a creek is present, representing a constant piezometric head.

The model runs using a selected timestep length (which can be sub-daily) for a period that is specified in the program parameters. Recharge is applied to each section of the flowtube in each timestep. Recharge represents long term values (ie. decades to centuries) rather than seasonal or annual values. Different sets of recharge can be applied for different 'blocks' of times to represent long term historical vegetation cover and climate factors.

3. FLOWTUBE CALCULATION

Flowtube assumes that all flow along the flowtube occurs through a conducting aquifer (Layer 1 in Figure 2). This aquifer is overlain by a semi-confining layer (Layer 2), within which lies the groundwater surface. Flowtube calculates head by stepping from one cross-section to the next down the tube, with the volume between any two sections being considered as a "cell". It is assumed that the groundwater head values (piezometric surface) used in the calculation are equivalent to the groundwater surface.

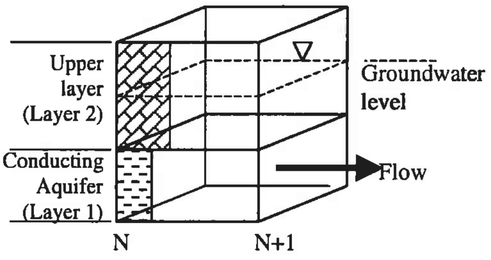


Figure 2. Flowtube cell conceptualisation.

The mass of an elemental volume (eg. of unit length) is:

$$\text{Mass} = A_1P_1 + A_2P_2 \qquad (1)$$

where A is the wetted cross sectional area, and P the Porosity, of the layers 1 and 2. On a unit length basis, the elemental volume is equal to the elemental mass. The change of volume over time (assuming that layer 1 remains full, and A1 is constant with time) is therefore given by:

$$dV/dt = P_2.dA_2/dt \qquad (2)$$

Darcy's equation gives the flux through layer 1 at any distance, x, along the tube as:

$$q = - A_1.\ K_1.dH/dx \qquad (3)$$

where K is the saturated hydraulic conductivity, H is the head. A finite difference form of (3) for flux between two nodes, N and N+1, is:

$$q=(A_{1,N}.K_{1,N}+A_{1,N+1}K_{1,N+1})(H_{N+1}-H_N)/2\Delta X \qquad (4)$$

For mass equilibrium, the rate of change in volume (with time) can be equated to the rate of change of flux (with distance), plus any recharge (R), thus:

$$dV/dt = dq/dx + R \qquad (5)$$

Inserting (2) into (5) gives:

$$P_2.dA_2/dt = dq/dx + R \qquad (6)$$

Expressing (6) in a finite difference form over timestep, Δt, from time t to t+1, gives:

$$P_2(A_{2,t+1}-A_{2,t})/\Delta t = (q_{N+1}-q_N)/\ \Delta X + R \qquad (7)$$

Rearranging (7) to solve for the new A_2 at time t+1,

$$A_{2t+1} - A_{2t} = \Delta t/P_2.[(\ q_{N+1}-q_N)/\ \Delta X + R] \qquad (8)$$

Flux, q, in (8) can be calculated using (4), and R, ΔX and P_2 are input parameters. Thus, having solved for the new wetted cross sectional area, A_2, the new value of head at any section is given by:

$$\Delta h = \Delta A_2/w \qquad (9)$$

where w is the width of the section. Thus:

$$h_{t+1} = h_t + (A_{2t+1} - A_{2t})/w \qquad (10)$$

Substituting equation (8) into (10) gives:

$$h_{t+1} = h_t+[(q_{N+1}-q_N)/\Delta X + R]/\Delta t\ /P_2\ /w \quad (11)$$

In Flowtube, the main calculation proceeds by first calculating flux for each cell, using (4), in order from the top to the bottom of the tube. The change in head at each section, using (11), is then determined, again proceeding from the top to the bottom section.

If the head in any timestep is greater than the surface elevation, then the head value is set equal to the surface elevation and the excess volume of water is removed as saturation excess flow. A maximum (vertical) discharge through the soil surface is imposed during simulations. If the calculated discharge exceeds this maximum, head is set equal to surface elevation, and the surplus volume of water is redistributed along the flowtube. The mass conservation of the model is checked at every time step, and a warning is provided when the mass is not balanced. Mass balance errors are saved to a text file for later examination.

4. DATA REQUIREMENTS

As noted previously, Flowtube requires a range of data, some of which are available from field measurements, and some of which need to be estimated by other means. These data include, for each section:

- Surface elevation;
- Groundwater surface elevation;
- Aquifer depth (above bottom);
- Aquifer bottom elevation;
- Aquifer width;
- Length to next section;
- Aquifer saturated hydraulic conductivity;
- Porosity of the upper layer;
- Recharge (for each of up to 50 sets, or 'blocks', of values),

and for the whole flowtube:

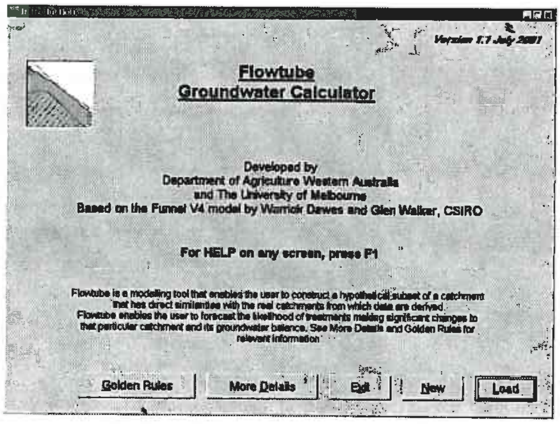
- Maximum groundwater discharge to the surface;
- Surface runoff across into the topmost cell, and the proportion of runoff that becomes recharge in this cell;
- Upper layer saturated hydraulic conductivity;
- Distance and head for the outlet boundary condition;
- Maximum surface evaporation and evaporation extinction depth, and
- A set of values the represent the effect of different management treatments (such as planting trees) on recharge.

These data are loaded into Flowtube from two input files. One file (treatment.csv) provides the management treatment effects on recharge, and the second (*.ftb) provides the remaining flowtube details for a given site or case study.

5. PROGRAM SCREENS

5.1 Program Introduction

The program opens with a temporary "splash" screen that identifies that parties that have contributed to development of the Flowtube program. The next screen (Figure 3) is a start-up screen that introduces the model.



Flowtube
Groundwater Calculator

Developed by
Department of Agriculture Western Australia
and The University of Melbourne
Based on the Funnel V4 model by Warrick Dawes and Glen Walker, CSIRO

For HELP on any screen, press F1

Flowtube is a modelling tool that enables the user to construct a hypothetical subset of a catchment that has direct similarities with the real catchments from which data are derived. Flowtube enables the user to forecast the likelihood of treatments making significant changes to that particular catchment and its groundwater balance. See More Details and Golden Rules for relevant information

Figure 3. Introduction screen of the Flowtube program.

This screen provides a brief introduction to the program and a set of links to relevant pages in the help file. Context sensitive help files can be accessed from all program screens. From this screen users can either load an existing case study file or create a new flowtube.

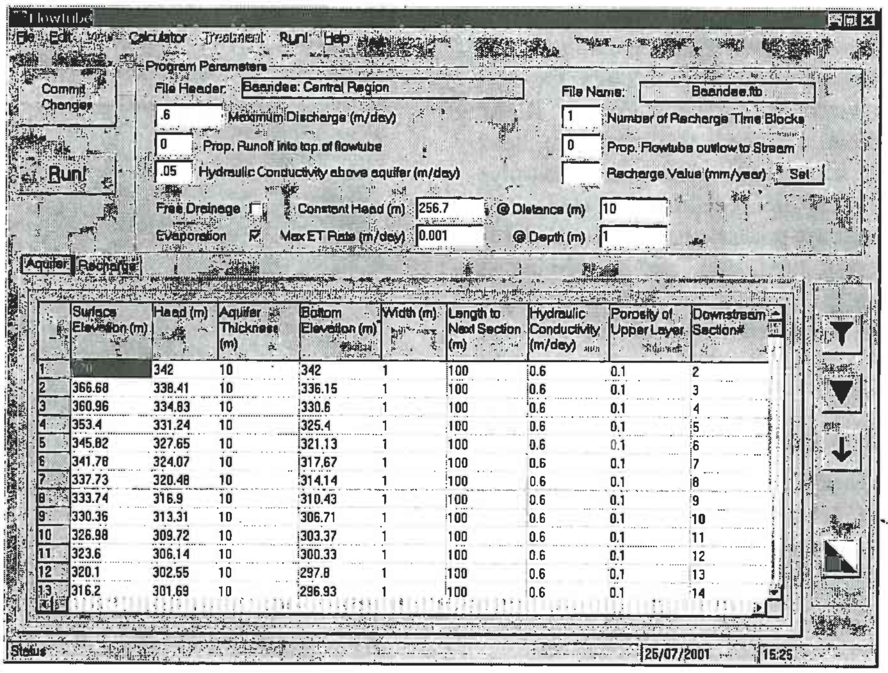
5.2 Main Screen

The Main Screen has two main sections. The Program Parameters section, in the upper portion of the screen, allows parameters to be viewed and edited. The lower portion of the screen shows a table with the flowtube input values (on the "Aquifer" tab) and the current recharge values (on the "Recharge" tab). To the side of this section are shortcut editing buttons for filling data in the table, and for toggling the data source (Figure 4)

Program parameters are:

- *Maximum Discharge (m/day):* The upper value for (vertical) discharge from the flowtube to the surface for each section.
- *Proportion of runoff into top of the Flowtube:* A portion of the surface runoff across the top cell (specified for each set of recharge data) can be input to the top cell. The remaining runoff is directly attributed to total stream runoff.
- *Hydraulic conductivity above the aquifer (m/day):* This value is combined with the aquifer hydraulic conductivity to calculate an effective hydraulic conductivity for flow within the aquifer. This is used to balance the assumption that the upper layer does not conduct water.
- *Number of recharge time blocks:* This value sets the number of blocks (or sets) of recharge to be used during a simulation.
- *Proportion of flowtube outflow to stream:* Some of the discharge out of the flowtube can be directly apportioned to streamflow using this value, in an attempt to match surface hydrographs. This amount of discharge is not included in the calculation of discharge to the surface from the flowtube for each section.
- *Recharge value (mm/year):* Shows to recharge value, in mm/year, for any recharge values selected in the recharge table. The "Set" button allows users to set a recharge value.
- *Constant Head (m) @ Distance (m):* These provide the outlet boundary conditions in cases where a free draining outlet flow is not selected.
- *Evaporation Parameters:* If evaporation calculations are active (the "Evaporation" check box is "ticked") then Flowtube applies evaporation to near-surface groundwater at a rate that varies linearly from the "Max ET rate (m/day)" for water at the surface, down to zero for water at the "@ Depth (m)". These values (Max ET Rate and Depth) are bounded by upper and lower limits that are stored in the flowtube input (*.ftb) file.

Running the model generally takes less than a minute on a reasonably powerful computer. The frequency of recording of output is automatically



Program Parameters

File Header: Beandee: Central Region

File Name: Beandee.ftb

.6 Maximum Discharge (m/day)

0 Prop. Runoff into top of flowtube

.05 Hydraulic Conductivity above aquifer (m/day)

1 Number of Recharge Time Blocks

0 Prop. Flowtube outflow to Stream

Recharge Value (mm/year)

Free Drainage ☐

Constant Head (m) 256.7 @ Distance (m) 10

Evaporation ☑ Max ET Rate (m/day) 0.001 @ Depth (m) 1

	Surface Elevation (m)	Head (m)	Aquifer Thickness (m)	Bottom Elevation (m)	Width (m)	Length to Next Section (m)	Hydraulic Conductivity (m/day)	Porosity of Upper Layer	Downstream Section#
1	[illegible]	342	10	342	1	100	0.6	0.1	2
2	366.68	338.41	10	336.15	1	100	0.6	0.1	3
3	360.96	334.83	10	330.6	1	100	0.6	0.1	4
4	353.4	331.24	10	325.4	1	100	0.6	0.1	5
5	345.82	327.65	10	321.13	1	100	0.6	0.1	6
6	341.78	324.07	10	317.67	1	100	0.6	0.1	7
7	337.73	320.48	10	314.14	1	100	0.6	0.1	8
8	333.74	316.9	10	310.43	1	100	0.6	0.1	9
9	330.36	313.31	10	306.71	1	100	0.6	0.1	10
10	326.98	309.72	10	303.37	1	100	0.6	0.1	11
11	323.6	306.14	10	300.33	1	100	0.6	0.1	12
12	320.1	302.55	10	297.8	1	100	0.6	0.1	13
13	316.2	301.69	10	296.93	1	100	0.6	0.1	14

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Figure 4. Flowtube program main screen.

set to produce 20 lines on the output screen, although this can be altered by the user prior to run initiation.

5.3 Results Screen

The Results screen depicts the groundwater levels over time (based on the output period), and, through selection of the "Hydrograph" tab, allows viewing of the groundwater hydrograph for any section (Figure 5)

The screen also shows:

- The length of flowtube at surface (ie.<0.01m) or at the maximum evaporation depth, if evaporation calculations are active. This uses whole section lengths, so is a coarse estimate.
- The length of flowtube within a certain, selectable, depth (0.5 - 5.0 m, in 0.5 m intervals) from the surface. This also uses whole section lengths, so is a coarse estimate.
- An extremely coarse estimate of the area of the catchment with groundwater at the surface based on a linear relationship (using a factor in the range 0.0 - 1.0, in 0.05 intervals) between proportion of flowtube at the surface (or at the maximum evaporation depth, if evaporation calculations are active) and the proportion of the catchment with groundwater at the surface.

This last estimate was provided to act as a reminder that the proportion of the length of the flowtube with water at the surface is *not* the same as the proportion of the catchment that may have near-surface water and so may become salt affected. This relationship depends largely on the shape of the catchment and the position of the flowtube that has been analysed.

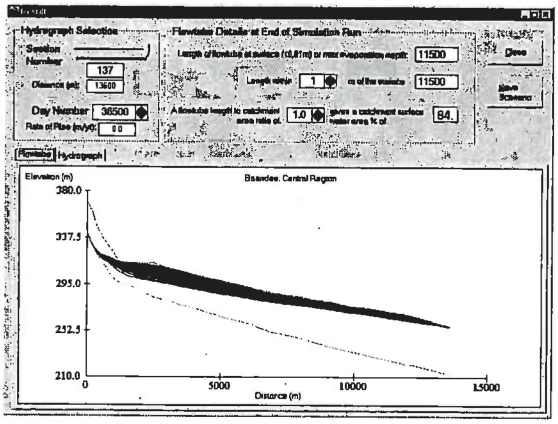

Figure 5. Results screen showing groundwater surface over time.

6. FLOWTUBE CONSTRUCTION TOOLS

There are a number of tools that assist in development of a new flowtube, or editing of an existing one. If users choose to construct a new flowtube, they are presented with an input screen for setting values of all the general program parameters, as well as setting the number of sections. Program execution then proceeds to the main screen (Figure 4) where aquifer and recharge values can be input directly, in a fashion similar to using a spreadsheet. Users typically enter only those aquifer values that come directly from field measurements. Note that there are generally considerably more sections in a flowtube than there are field measurements.

Three tools are provided for filling cell values between sections. These are provided by three buttons to the right of the aquifer table, and are also available via main and pop-up menus. These tools are:

- **Interpolate** - fills data between two values on the table, using interpolation based on the distance between the sections.
- **Linear Fill** - fills data between two values on the table, using interpolation based on the number of gaps between the sections.
- **Fill Down** - fills between two cells in a column, using the value in the upper cell.

Identification of the sections with data that come from field measurements is done via the "toggle" button (lower, right on the screen) that turns adds or removes a small blue square in the Surface Elevation column.

When values have been entered on the aquifer table, it is possible to view and edit these via a longitudinal section, or 'mesh' of the flowtube, showing basement, aquifer depth, groundwater surface and ground surface (Figure 6).

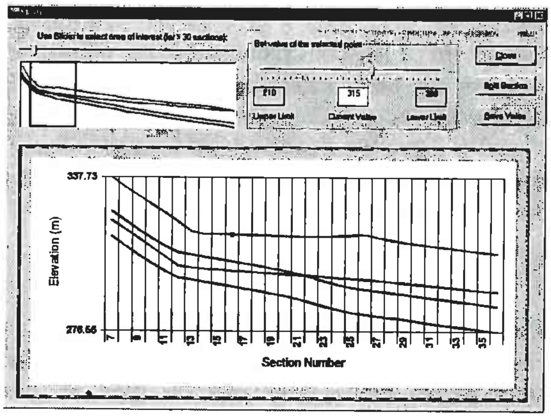

Figure 6. Flowtube mesh editing screen.

The 'Mesh' screen allows values to be directly edited through a 'slider' bar, in the upper right of the screen, which varies values between two extremes. Extra sections can also be added to the flowtube from this screen.

With these tools it is simple and quick to build a simple flowtube, provided the required data are on hand.

7. ANALYSIS AND EXPORTING

There are a range of options for analysing and exporting run output from Flowtube. Values of surface and stream discharge, and head, from a model run can be viewed for each output time and each section, and can be exported to text files.

The final groundwater surface, and length of flowtube at, and near, the surface can be saved and compared for up to five runs, using the "Save Scenario" option from the Results Screen. These scenarios can be viewed on a separate screen, and can be exported to a text file for further graphing and comparison.

8. TESTING, CALIBRATION AND DEVELOPMENT

Some formal checking of the Flowtube, and Funnel, code has been undertaken, with two external reviewers checking that the code accurately represents the algorithms provided in Section 3.

Calibration of each case study is possible in a limited way, by checking whether the rates of rise (or fall) of groundwater during the first few years of calculation, match the values that have been measured in the field. Testing of model operation and flexibility has involved having a number of experienced field researchers run the program for known field situations and compare the output values with those they have measured or estimated.

Further to this, construction of the flowtube program has been undertaken using a process of interface prototyping [Argent and Grayson, 2001], whereby users are involved in workshop-based development and testing that allows changes to the program interface to be tested in real time.

9. CONCLUSION

The Flowtube program provides a useful extension tool with a scientifically acceptable groundwater model that can be used in the management of dryland salinity. By providing information relevant to the needs of catchment managers and extension staff, the Flowtube program is a useful tool for the exploration of alterative options in salinity management. Extension of the tool from its Western Australian origins, to the rest of Australia, is now being undertaken through a project supported by the Grains Research and Development Council and Land & Water Australia.

10. ACKNOWLEDGEMENTS

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