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User's manual for the distributed recharge model ZOODRM

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INTERNAL REPORT IR/04/150

User's manual for the distributed recharge model ZOODRM

M.M. Mansour and A.G. Hughes

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Foreword

This development of the ZETUP, ZOOMQ3D and ZOOPT modelling software has been undertaken through a continuing tripartite collaboration between the University of Birmingham, the Environment Agency and the British Geological Survey. The recharge model ZOODRM has been developed by the British Geological Survey. The development of ZETUP and ZOOMQ3D was initially undertaken at the University of Birmingham between 1998 and 2001 but continued after this time as a collaborative project between the three partner organisations. Since the inception of the collaborative project, the development of the software has been directed by the ZOOM steering committee, the members of which are:

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Dr Andrew Spink

Environment Agency

Steve Fletcher

Paul Hulme

British Geological Survey

Dr Denis Peach

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Dr Chris Jackson

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Preface to the second edition

This second edition of the ZOODRM manual complements the release of version 1.01 of the recharge model code. To run version 1.01 of the recharge model using the files prepared for version 1.0, some of the input files need to be modified. These are the main input file (Section 5.9.2, Table 22), the main rainfall file and associated files related to the raingauge stations (Section 5.2, Table 6 and Table 7) and the main evaporation file (Section 5.3, Table 8). The main alterations to the previous version of the model are:

- Adjustment of the input files so that all grids are referred to by the co-ordinates of their lower left corner.
- Addition of the possibility of selecting between runoff coefficient values that either vary on a monthly basis or are related to the rainfall intensity and the soil moisture deficit.
- Modification of some of the output files for ZOOMQ3D compatibility
- Minor bug fixes.

Preface to the third edition

This third edition of the ZOODRM manual complements the release of version 1.02 of the recharge model code. To run version 1.02 of the recharge model using the files prepared for version 1.01 the “raingrid.dat” input file needs to be modified (Section 5.2, Table 6). A single alteration is made to this file. This is:

- The default substitute raingauge station is defined at the line following the lines describing the details of rain gauge stations.

Preface to the third edition (N)

This third edition (N) of the ZOODRM manual complements the release of version 1.03 of the recharge model code. Version 1.03 of the model incorporates adjustments to the code to add flexibility for setting values of some of the input parameters and to improve the format of some of the output files. To run version 1.03 of the recharge model using the files prepared for version 1.02 an additional input file “runoff.asc” needs to be added (Section 5.1.10). The changes that have been made are described in the following bulleted list:

- Runoff and Run-on coefficients are related to a new ASCII file “Runoff.asc” (Section 5.1.10).
- The model produces the locations of ponds in a file named “pond##.out” where the ## represents the grid number where ponds are located (Section 6.2.5).
- The model reads from an input file named “aspect.dat” the aspect directions at a user defined locations (Section 5.9.5).
- A comment line and a flag is added to the input file “input.dat” to include aspect correction if required (Section 5.9.2).
- A new format of “rech.tv” output file when stress period approach is used. The new format of “rech.tv” matches the format of this file when blocks of years are used.
- The format of “rech.db” output file is corrected. Note: this file is not produced if the time stepping is different from days months and years.
- Runoff routing output is modified. River flows are produced in Ml day^{-1} rather than mm day^{-1} .
- A new output file “dailyrech.tv “ is added to produce gridded daily recharge values. The time during which the gridded recharge values are produced must be set in the control file “output.dat” (Section 5.9.3).

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PART 1 - Background

1 Introduction

1.1 WHY DISTRIBUTED RECHARGE?

An analysis of recharge, i.e. the quantity of water that infiltrates from the land surface to the aquifer, is an essential step in determining the resources of a groundwater system and simulation of flow in aquifers. Recharge is a complex process, but its quantification is important in order to understand the total water availability from an aquifer. A groundwater model constructed to simulate groundwater flows in a regional aquifer is usually coupled with a distributed recharge model. The need for a distributed recharge model in such a case stems from the fact that the factors affecting the recharge calculations vary temporally and spatially at a regional scale. In addition, distributed recharge models enable the groundwater models to calculate heads and flows at the required point (i.e. nodes for Finite Element and Finite Difference based models) and for the appropriate time steps, (Hughes et al., 2003). Estimates of recharge, therefore, have to be distributed in time and space. A distributed recharge model has been developed for this purpose using object-oriented techniques. This model is called ZOODRM (zoom object-oriented distributed recharge model).

1.2 WHY OBJECT-ORIENTED APPROACH?

The model user is not directly affected by the approach used to develop the model. The user's main interest is the functionality incorporated in the model to solve the problem under consideration. The user is also interested in the ease and flexibility of processing the input and output data of the numerical model. The functionality implemented in a numerical model could be sufficient for one specific application or may adequately represent the current understanding of recharge mechanisms in general. This understanding, however, evolves with time, and different approaches to represent a recharge mechanism may be developed. In addition, the mechanisms, currently implemented in the model, may not fulfil the user needs. Under these circumstances, the involvement of the user in the code development is crucial for the incorporation of new approaches or for code enhancement. The overall aim of the recharge model is to be flexible enough to cope with recharge processes that vary spatially over a study area and be able to change during a project as understanding increases.

The flexibility and power of object-oriented programming are generated from the possibility of updating the code as the understanding of recharge processes develops. Objects created in an object-oriented code are representations of real world items. Recharge, for example, is calculated at node objects representing area of the system. Nodes can then be assigned different types of recharge calculation method. These items are easily identified in an object-oriented code and form the basis building blocks of the model (Spink et al., 2003). Another example is the data objects created in the model can be removed and replaced by other more sophisticated objects. Gridded data objects, for example, can be replaced by software data objects such as ArcGIS objects or a statistical rainfall object could be used instead of the current data based rainfall object.

1.3 THE RECHARGE MODEL

The recharge calculation in the model is undertaken on a distributed basis that exploits OO techniques. There are four different types of node objects. These are recharge, unsaturated, river and spring node objects. Node objects, such as the recharge and unsaturated node objects, are held on grid objects, the river node objects, on the other hand, are connected using a linked structure as if they represent one physical object, while the spring node objects are independent of each other. There are two layers of grid objects; the upper grid holds the recharge node objects and overlays the second grid object which holds the unsaturated node objects.

Recharge nodes deal with objects that represent the land surface and the atmospheric characteristics of the area. They can be allocated different types of land usage and given different types of recharge calculation using inheritance. In principle, any number of recharge node types can be specified. Currently there are five types of recharge nodes which implement the following methods:

- (i) Soil moisture deficit recharge calculation,
- (ii) A method incorporating crop water requirements and based on a concept developed by the UN Food and Agriculture Organisation (FAO),
- (iii) An arid zone accounting method,
- (iv) A method that calculates recharge from urban areas and,
- (v) A method that calculates recharge from irrigated areas.

The recharge node objects also interact with the river node objects to represent runoff and its discharge outside the area.

The unsaturated node objects are responsible for the movement of the infiltrated water in the unsaturated zone. This is represented by either the communication of these nodes with the spring node objects, i.e. passing water to them, or by setting the delay time that may occur in this zone.

In addition to the recharge calculation objects, there are data objects which hold distributed atmospheric and land information. The data objects read data on grids that area independent of the calculation grids enabling the model size to be changed without the need to alter the data grids. These data objects represent, for example, topography, geology, landuse, rainfall, and evaporation.

1.4 TERMINOLOGY

ZOODRM is written using an object-oriented programming language. Whilst the users do not need to concern themselves with what this means, the term *object* is used a number of times within this manual and consequently, a brief explanation is required.

The user can think of an object in abstract terms as any distinct entity that stores data and perform tasks. In ZOODRM objects are defined to represent real world features. For example, the soil zone is represented by an object.

1.5 UNIT CONVENTION

All lengths in ZOOMDRM must be specified in metres. The unit of time is specified as days. Parameters representing the plants and ground characteristics are in mm. Rainfall rates are defined in mm day^{-1} when input and potential evaporation defined as mm month^{-1} .

2 Modelling approach and key concepts

2.1 OBJECT FRAMEWORK

The distributed recharge model requires that the recharge calculations are undertaken at the appropriate points over the study area. A daily time-step is used for the recharge calculation, with the output supplied as monthly averages. The recharge calculation is undertaken within a node object. These node objects are held, in turn, within a grid object. Any number of grids can be specified at whatever scale is required. This facility was developed to provide input data in the correct form for ZOOMQ3D, which incorporates local grid refinement in a Cartesian mesh (Jackson, 2001).

Data are stored in separate objects for each data type, e.g. rainfall, potential evaporation, etc). The node object can then access data from the appropriate data object by sending its position (X and Y co-ordinates) and time (day, month and year). The data value for that position and time is then determined and returned to the node object. Although both the data and the node objects are grid based, each data grid is independent from each other and the nodal grid. This ensures that the nodal grid can be changed without the need to recalculate the distribution of data nodes. However, if any of the data grids are coarser than the calculation grid, then the nearest node in the data grid will be used.

The recharge model relies on data sets that are held within a GIS environment. Most of the data, which are exported from the GIS as ascii arrays (i.e. grid files), are directly read by the recharge model. In some cases, data has to be either processed using a spreadsheet or reorganised in a suitable format for the model to read. An example of the latter case is the preparation of the data file "Plants.dat" that holds the information about the percentage area of the grid node area a crop covers.

The relationship between the objects (i.e. the framework) is illustrated by Figure 1. The main object is ZOODRM which holds all the other objects. This object initiates all calculation and data objects. For example, it initiates the grid objects (both the recharge and unsaturated grid objects) which in turn create the calculation nodes, it initiates the river and spring objects if they exist, etc. The objects that are derived from a base class are mentioned in a box within the base class. The control of the time-step and storage of the date is handled by the clock object (CClock).

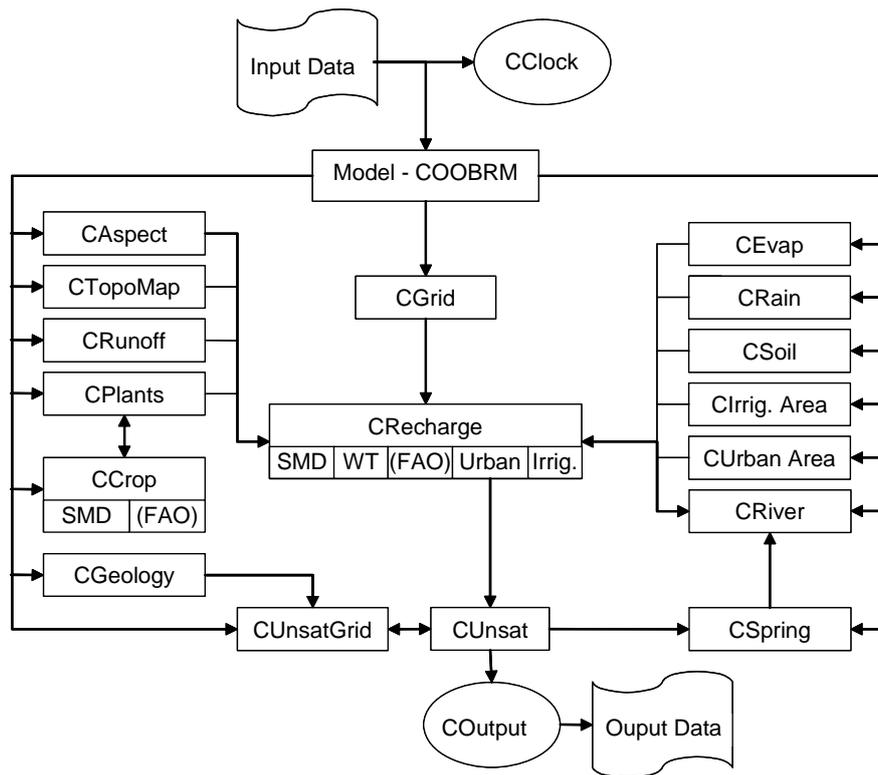


Figure 1 Framework of the recharge model

2.1.1 Description of objects used within the model

There are three different types of objects handled by the model. These are the calculation objects, which are responsible for quantifying the components of the recharge mechanisms, the data objects, which hold the spatial and temporal information, and other objects for managing the calculations and producing the results. The main objects created in the current model are as follows:

- Calculation objects
 - ZOODRM – model object that handles creation of all other objects, time stepping and calculation of recharge via Grids
 - CGrid – object that holds CRecharge objects where recharge calculation takes place
 - CUnsatGrid – object that holds CUnsat objects and stores recharge calculated at each nodes
 - CRecharge – object where recharge calculation takes place
 - CUnsat – object where the effects of the unsaturated zones are taken into consideration.
 - CRiver – object that determines how runoff is routed using slope aspect from a digital terrain model (DTM) and discharges the flow to the outside of the considered area.
 - CSpring – object that holds spring flow information and calculates spring flows

- Data objects
 - CRain – inputs and stores rainfall on a grid basis and distributes via LTA rainfall, or inputs information from a set of data files.
 - CEvap – inputs and stores Potential Evaporation (PE) on a grid basis
 - CGeology – Stores information that are accessed by unsaturated node objects.
 - CPlants – create and organise information about Crop objects. This object also stores landuse data.
 - CSoil – stores WT values and other soil information to be used by the application of the (FAO) recharge calculation method
 - CCrop – stores landuse data based on crop type. Information held in this object are used if the SMD or the (FAO) recharge calculation methods are applied.
 - CTopoMap – stores the Land surface elevations
 - CAspectMap – stores data for aspect directions at the recharge nodes.

- Other objects
 - CClock – handles time-step and updates date
 - COutput – object that manages the output files of the models.
 - CUrbanAreaGrid – holds and create urban area objects
 - CIrrigatedAreaGrid – holds and create irrigated area objects
 - CRechargeMap – indicates which recharge method to apply. This could be 1 for SMD, 2 for WT or 5 for (FAO) recharge methods. Irrigated and urban areas overwrite the information given here if they exist at the considered node location.

2.2 KEY CONCEPTS

The calculation of recharge within ZOODRM can be briefly summarised as follows: at the beginning of each time step, the calculations start at the recharge node level. The recharge nodes request data from the data objects through Grid and ZOODRM objects. The data are then processed by the recharge nodes which calculate the runoff and recharge values. The runoff calculated at one recharge node is passed from one recharge node to another until it is delivered to the river node object. The calculated recharge is passed directly to the unsaturated node object where it is split into two parts. The first is passed to the spring object which, if created, discharges it to the corresponding river node object. The second part is stored at the unsaturated nodes as recharge.

The total water calculated at the river nodes and resulting from the surface routing and spring flows is routed downstream and considered as the surface water flow. It is assumed that the river objects loose part of this water to the unsaturated nodes, which add this water to the recharge water already stored there. The calculations stop at this stage and the total water calculated at the unsaturated node is then considered as the final recharge value at this time step. Topographical depressions are considered as ponds. The model determines these pond nodes based on the aspect map. A river node overrides a pond node if they overlap. The relationship between the calculation objects is illustrated in Figure 2.

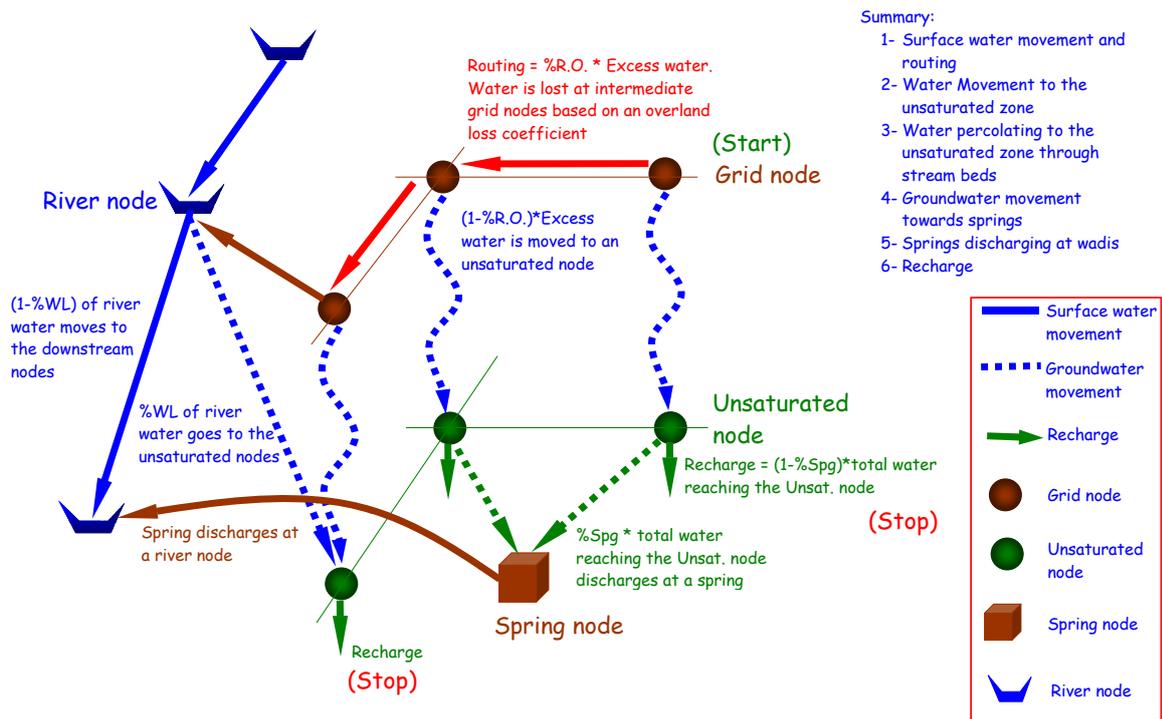


Figure 2 Outline of the calculation procedure

2.2.1 SMD method

The conventional method of estimating recharge in humid areas is based on the work of Penman (1948) and Grindley (1967). This method calculates the recharge as the excess quantity of water available from rainfall after taking the runoff, the potential evaporation and the soil moisture deficit into account. Runoff is assumed to take place instantly after rainfall and its quantity is estimated as a fraction of the amount of rainfall. The potential evaporation is the maximum quantity of water that can evaporate under the given conditions of wind speed and solar radiation.

The Penman equation is usually used to determine the potential evaporation. This equation includes the value of evaporation from grass-covered soil with a freely available supply of water. If the value of the potential evaporation is, therefore, greater than the quantity of water minus the quantity of runoff, water will be lost from soil by evapo-transpiration by plants. However, the quantity of water lost from soil is dependent on the Soil Moisture Deficit (SMD), which is the amount by which the soil moisture is below the field capacity, of the soil. This technique calculates the change in Soil Moisture based on a relationship between Actual Evaporation (AE) and Potential Evaporation (PE). The relationship between AE and PE is derived from the Soil Moisture Deficit in relation to the Root Constant (C) and Wilting Point (D) as described in Figure 3. Water is assumed to be freely available from the part of the soil located between the ground surface down to a horizon equivalent to the value of C, but only part of the water can be extracted from the soil when the SMD reaches or becomes greater than the value of C. No water is extracted from the soil if SMD reaches or becomes greater than the value of D. In the latter case, the value of SMD is considered to be equal to the value D.

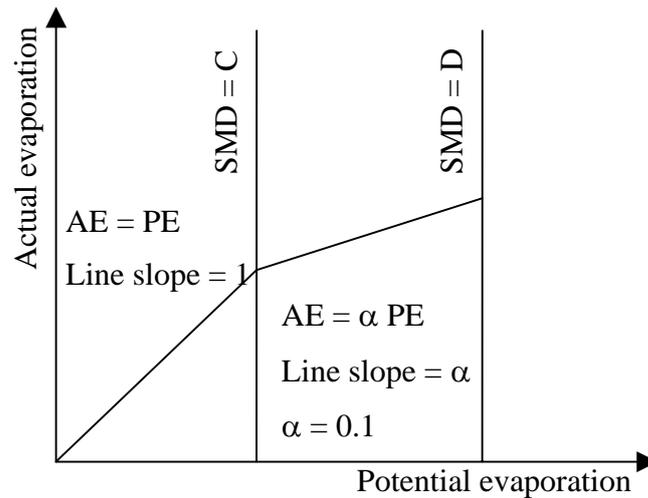


Figure 3 Relationship between Actual Evaporation and Potential Evaporation

When the SMD reaches a value of zero, the excess quantity of rainfall is considered as potential recharge. The mathematical representation of this recharge calculation method can be summarized as follows:

1. Calculation of Actual Evaporation

If $SMD < C$ or $R \geq PE$: $AE = PE$

However, if $C < SMD < D$ and $R < PE$: $AE = R + (EF \times (PE - R))$

Where EF is an empirical factor and tends for Evaporation Factor. It is represented by the symbol α in Figure 3.

For all other cases $AE = R$

2. Calculate the SMD

$$SMD_{n+1} = SMD_n + AE - R$$

3. Calculate the potential recharge

If $SMD < 0$: Recharge = $-SMD$

Where:

R Rainfall (L/T)

PE Potential evaporation (L/T)

AE Actual evaporation (L/T)

C Root constant (L)

D Wilting point (L)

SMD Soil moisture deficit (L)

2.2.2 Wetting Threshold Method

The application of the conventional (SMD) method to estimate recharge for areas in arid and semi-arid regions is not possible because the soil moisture is often not at its field capacity. This prohibits the instant occurrence of runoff and causes additional water losses to occur. Besides, in uncultivated areas of semi-arid regions, vegetation may develop at the end of the wet season and die within a short period, and after a long dry period, the effect of evapotranspiration from the dried vegetation is minimal.

Lange et al. (2003) investigated the potential recharge in semi-arid areas by undertaking sprinkler tests in a study area within the West Bank, Palestine. This study showed that no runoff is generated from rainfall over dry soil until a certain amount of rainfall is exceeded. This contradicts with the assumption of the instant occurrence of runoff as implemented in the conventional method of recharge calculation. In addition, once the runoff appears on the surface, its rate, as a percentage of the rainfall intensity, increases gradually and reaches a constant value, which, in the experiment is equal to 85% of the rainfall intensity. A recharge method to reflect the findings of this experiment was developed, this recharge method is called the wetting threshold method.

In the wetting threshold method, the effective precipitation (EP) is calculated as the difference between rainfall and potential evaporation. If EP is positive, the rainfall value is larger than the potential evaporation, and excess water is available to compensate the soil moisture deficit and to generate runoff and recharge. First a wetting depth (WD) will develop from the ground surface downwards. If this wetting depth exceeds a certain value water becomes available for runoff and recharge. The maximum value that WD can reach is called the soil threshold (ST). ST is defined as the maximum amount of water that is absorbed by the soil before any runoff is generated. Excess water in this case is calculated as the difference between WD and ST. The maximum value WD can reach is equal to ST and the recharge and runoff are calculated as percentage of this excess water. If EP is negative, and WD is greater than zero, it is assumed that water is freely available to evaporate and the SD value is set accordingly.

The calculation method is as follows:

1. Calculation of the effective precipitation (EP):

$$EP = P - PE$$

2. Calculation of the wetting depth WD:

- If $EP < 0$: $WD_{n+1} = WD_n - ABS(EP)$ and $WD_{Minimum} = 0.0$
- If $EP > 0$: $WD_{n+1} = WD_n + EP$

However, if $WD_{n+1} > ST$, there is excess water (EW) given by: $EW = WD_{n+1} - ST$

and $WD_{Maximum} = ST$

3. Calculation of the potential recharge (R)

- If $EP < 0$: $R = 0.0$

If $EP > 0$: $R.O. = EW * R.O.C$ and $R = EW * (1 - R.O.C)$

Where:

- P Precipitation (L/T)
PE Potential evaporation (L/T)
WD Wetting Depth (L)
EW Excess Water (L)
SD Soil Threshold (L)
R Recharge (L/T)
R.O. Runoff (L/T)
R.O.C Runoff coefficient (-)

2.2.3 Environment Agency/FAO method

A review of recharge estimation for British aquifers carried out by Rushton (2000) includes the development of a new soil moisture balance recharge estimating approach. This method relates the soil moisture deficit value to the water content of the soil and the crop water requirements to calculate the evapotranspiration and the recharge. The evaporation from bare soil is also considered. This method is described briefly in this section. A full description can be found in the Groundwater Resources Modelling: Guidance Notes and Template Project Brief (Version 1) document prepared by the Environment Agency (EA) (EA, 2002).

This method uses a better approach to calculate the evapotranspiration of plants. In addition, similar to the conventional SMD method, the recharge calculation is also based on the SMD level; however, the temporal changes of the crop and soil characteristics are taken into consideration.

The calculations start by firstly defining a potential evaporation of a reference crop ET_0 . The potential evaporation of any crop is then given by $ET_c = K_c ET_0$ where K_c is the crop coefficient. To determine if the considered crop can transpire at the potential rate, the SMD level is compared to two parameters that are dependent on soil and crop characteristics. The first parameter is the Total Available Water (TAW), which is given by $TAW = 1000(\theta_{FC} - \theta_{WP})Z_r$.

where:

- θ_{FC} Moisture contents at field capacity
 θ_{WP} Permanent wilting point
 Z_r Root depth

The second parameter is the Readily Available Water (RAW) where RAW is approximately 40 to 60% of TAW. If the SMD level is less than RAW, the plants transpire at the potential evapotranspiration rate. If SMD is greater than RAW, the plants transpire at a reduced rate equal to $ET = K_s (Et_c)$ where K_s is called the soil stress coefficient and varies from 0 to 1 based on the SMD value as illustrated in Figure 4. The plants do not transpire if the SMD value is greater than TAW. A relationship between K_s , RAW, TAW and SMD can be

established from Figure 4. This is given by: $K_s = \frac{TAW - SMD}{TAW - RAW}$

If the soil is bare, the potential soil evaporation (ES) is given by $ES = K_e ET_0$ where K_e is the evaporation coefficient which is usually set to 1.1. The actual soil evaporation is given by $K'_s ES$ where K'_s is an alternative soil stress coefficient which is determined as K_s but from two parameters, the Total Evaporable Water (TEW) and the Readily Evaporable Water (REW). The first parameter is given by the following equation $TEW = 1000(\theta_{FC} - 0.5\theta_{WP})Z_e$ where Z_e is the depth of the surface soil layer that is subject to drying by evaporation. The permanent wilting point is multiplied by a factor of 0.5 because it is assumed that the evaporation can dry the soil to mid-way between the wilting point and oven dry.

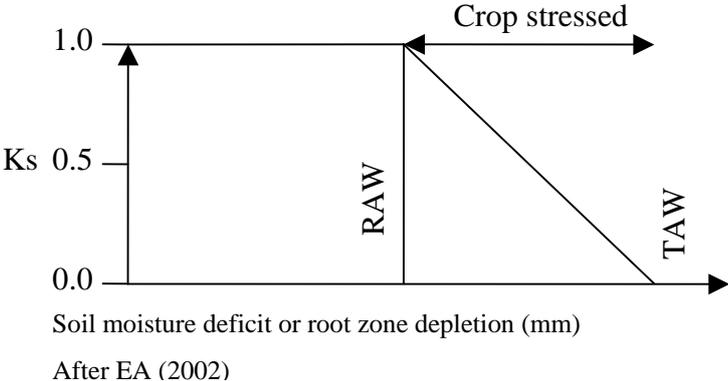


Figure 4 Relationship between Actual Evaporation and Potential Evaporation

The crop coefficient (K_c), the root depth (Z_r) and the percentage crop cover (Max Cover) change based on the crop growth status. The times at which the crop goes from one status to another have to be specified. In the current method these times are: the harvest time, the drilling time, the time when crop starts to emerge, the time when the crop covers 100% of the area and the time when senescence begins. The above three factors are then determined knowing the current time as explained in the diagram of Figure 5.

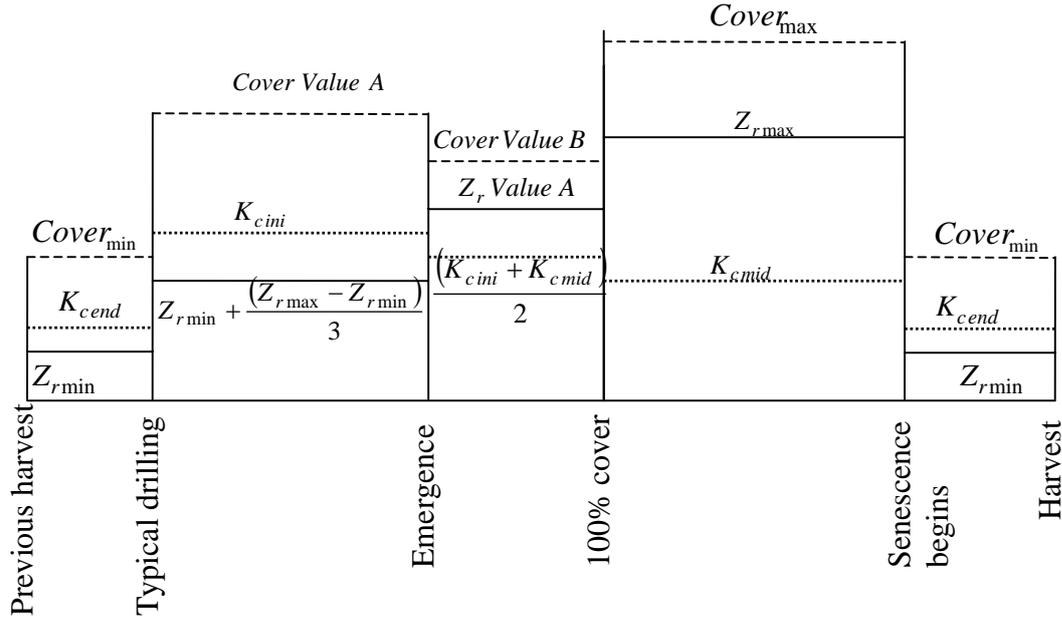


Figure 5 Diagram explaining the calculations of the Root depth (Z_r), the crop coefficient (K_c) and the crop cover.

where:

$$Cover Value A = Cover_{max} - (Cover_{max} - Cover_{min})/3,$$

$$Cover Value B = Cover_{max} - (Cover_{max} - Cover_{min}) * 2/3 \text{ and}$$

$$Z_r Value A = Z_{rmin} + (Z_{rmax} - Z_{rmin}) * 2/3$$

The different recharge scenarios can be represented mathematically as follows:

1. Estimation of the actual evapotranspiration

For $SMD_n < RAW$ or for $In \geq PE$, then $AE = PE$

For $TAW \geq SMD_n \geq RAW$ and $In < PE$, then $AE = In + K_s(PE - In)$ where:

$$K_s = \frac{TAW - SMD_n}{TAW - RAW}$$

For $SMD_n \geq TAW$ and $In < PE$, then $AE = In$

2. Soil moisture balance and calculation of potential recharge

$$SMD_{n+1} = SMD_n - In + AE$$

If $SMD_{n+1} < 0.0$, $RECH = SMD_{n+1}$ and $SMD_{n+1} = 0.0$

2.2.4 Urban Areas

Urbanisation provides an additional component of groundwater recharge generating from the loss of water from water supply and waste water pipes. Rainfall recharge, on the other hand, decreases due to hardstandings and roofs which divert rainwater to drains. All engineering practices aim to minimise the leakage from sewers, but some unforeseen factors such as extra road loading, etc. may crack the sewers and result in unwanted losses.

The framework of recharge calculation in urbanised area is illustrated in Figure 6 and is summarised as follows. The model assumes that urbanised areas constitute two parts. The first is a paved or an impermeable part that represents roads and buildings. The second is a green area that represents parks and domestically cultivated areas. The percentage of the impermeable area is a user-defined number, and the percentage of the green area is determined accordingly.

Two sources of recharge water are identified in this case. The first is recharge from water mains and sewers that is calculated as a percentage of the daily water supplied to the area. The second is the recharge from the grassed part and based on the application of the conventional SMD method. In the latter case, recharge is resulting from rainfall only and all factors such as evaporation, effect of soil zone, etc. are taken into consideration. The SMD calculated recharge is factored by the percentage of the area of the green part to the total urban area and added to the recharge resulting from water mains and sewer leakages. The total calculated recharge is then passed to the unsaturated zone.

Unlike the other recharge nodes, all urban area nodes are assumed to discharge the calculated runoff to one stream node. This is to represent the fact that in urban areas, runoff water is directed through storm water pipes that discharge at one specific location

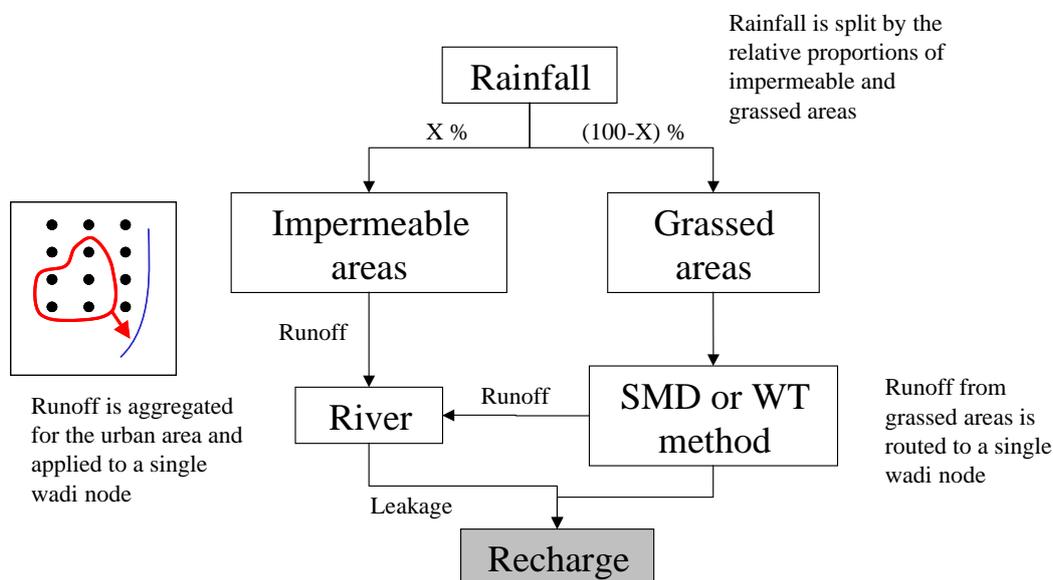


Figure 6 Recharge calculation for urbanised areas

2.2.5 Irrigated Areas

Irrigated nodes are SMD type recharge nodes but that receive, in addition to rainfall during the wet season, a specified quantity of water during the dry season. But, unlike the SMD recharge nodes, there is only one crop object associated with each irrigated area with one root constant value (C) and one wilting point value (D). During the wet season, the SMD recharge calculation method is applied. During the dry season, it is assumed that a fixed percentage of the applied water, representing the transmission losses, infiltrates directly to the unsaturated zone. The remaining water is then split into two parts. The first is the runoff water which is routed to the nearest river node based on the aspect direction map, and the SMD recharge process is applied to the second part to calculate the amount of water that infiltrates to the unsaturated zone.

2.2.6 Routing to Rivers

The amount of flow in the river branches is partly controlled by the runoff coefficients that are allocated to the recharge nodes. The Runoff coefficient can be varied on a monthly basis or can be related to the soil conditions. The relationship between the runoff coefficient, rainfall intensity and current soil moisture deficit developed by Rushton (2003) for cultivated sandy soil overlying sandstone aquifer is hard-coded in the model. The runoff coefficient represents the percentage of the rainfall to be routed to the rivers. The routing procedure is based on an aspect map created in a GIS environment. This map indicates the direction of the slope of the ground surface at each recharge node. The runoff water is moved from one node to the adjacent one based on this direction. When a recharge node that is connected to a river node is reached, the river flow at this node is incremented by the amount of the runoff flow.

It is assumed that the runoff flow, generated at one node, diminishes in quantity before moving to the next node. In the recharge model, this is represented by an overland loss factor which is defined as the fraction of the runoff water generated from one node and lost over another (Figure 2). This factor, called run on in the model, depends on the physical characteristics of the rocks, or the soils over which the water is moving and is defined as the loss of water per metre length, i.e. this factor has a unit of m^{-1} . Water loss is therefore dependent on the distance travelled by the runoff within a surface water catchment. It should be noted that the product of run on coefficient and the maximum cell length in the model must be less than one. The total run on flow calculated at one node during one time step is considered at the next time step (i.e. the next day) and is added to the rainfall amount of the next time step. Topographical depressions are considered as ponds. The model determines these pond nodes based on the aspect map. The surface water routing can be interrupted and may not reach the river node if a pond node exists between the two nodes. The surface water routed from one recharge node will be lost completely as recharge at a pond node.

2.2.7 Springs

Springs occur at locations where the water table intersects the ground surface. The groundwater flow to springs is dependent on the hydraulic gradient, the hydraulic conductivity of the aquifer material and the distance between the water source location and the spring. It is extremely difficult to determine the groundwater movement within an aquifer and to determine the catchment related to a spring without the consideration of detailed geological and mathematical models. Since it is not possible to include these features in a recharge model, an alternative approach to represent springs has been found.

It is assumed that part of the recharge flow that reaches an unsaturated node discharges at a spring providing that the unsaturated node is connected to the spring. Springs are represented in the model as objects that are connected to the unsaturated node objects based on the following criteria:

1. The ground elevation of the unsaturated node has to be higher than the elevation of the spring. This ensures that the springs do not receive water from locations with ground elevations less than the spring elevation.
2. The spring connects only to unsaturated nodes that have specific geological and hydrogeological characteristics.
3. There is no topographical depression with ground elevation less than the spring elevation along the straight line that connects the spring to the unsaturated node.
4. The distance between the unsaturated node and the spring is less than a specified value.
5. If an unsaturated node satisfies the above conditions for more than one spring, it connects to the nearest spring.

PART 2 – Model input

3 Running the model

All that is required to install ZOODRM on a Windows PC is to copy the executable 'ZOODRM.exe' into a working directory. No installation procedure is run in which ZOODRM program files are added to the system registry. All the input files required by ZOODRM must be located in the same directory as the executable file. All output files produced by ZOODRM will be created in the same directory as the executable file.

ZOODRM should be run from the command line in a MS-DOS style box and not started from Windows Explorer. In the event that an error occurs, messages are written to the screen. If ZOODRM is run from Explorer it may terminate before the user is able to read error messages. To start a command window select 'Run' from the Windows start menu and type either 'cmd' or 'command' in the drop down list box (Figure 1). The user should then change directory to that of the working directory where the ZOODRM executable file is located. To run the model type 'ZOODRM' on the command line.

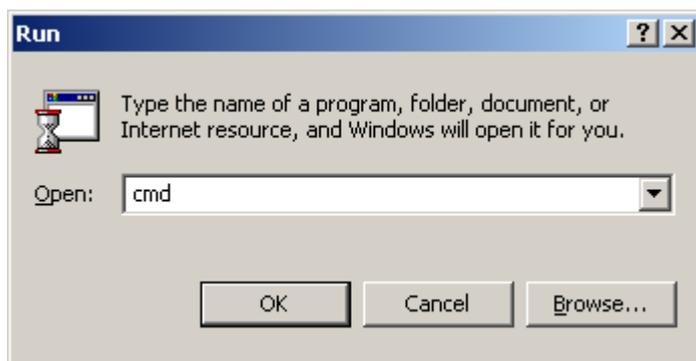


Figure 7 Starting a command line window from the Windows start menu

4 Summary of input files required by ZOODRM

4.1 THE PHILOSOPHY OF MODEL INPUT

The philosophy behind the structure of ZOODRM model input is to separate different types of data between files. That is, each file contains one specific type of information only. Whilst this results in the model requiring many input files compared to other models, they all have a very simple format and are easily modified using a text editor. The following points should be recalled when modifying ZOODRM input files:

1. Values are read into the model in 'free format' and consequently, the user does not need to ensure that the number of decimal places and field width are correct for each input value contained in each file.
2. The correct number of parameters must be entered on the correct line of an input file.
3. Whilst it does not matter whether the user enters a decimal number as an integer, it is not permissible to enter an integer as a decimal number.
4. Some but not all files contain comment lines. These are text strings, which are read by the model and discarded.
5. The maximum length of a comment line is 128 characters.
6. It is good practice but not necessary to remove white space from the end of lines.
7. Comments cannot be appended to the end of lines of data. If these are included the model will crash.
8. Comments can be appended to the ends of files.
9. The names of all files are fixed, except where defined in datafiles.

The list of input files required by ZOODRM is presented in Table 1 and are grouped into categories. Though there are 29 files listed, not all of these are required for all simulations. The files are listed by mechanism in Table 2 and are cross-referenced in this table to the relevant section in this report. Each of the ZOODRM input files is described in the following section.

The nodes in ZOODRM are created from the information contained in the file grids.dat. This file is created by ZETUP, the pre-processor to ZOOMQ3D. This ensures that the recharge model calculates recharge in exactly the same place as nodes in the groundwater model. The file recharge.asc, which is produced by ArcView, contains an areal distribution of recharge calculation node types. Currently, there are five node types in the model:

1. Soil moisture deficit approach
2. Wetting threshold method for semi-arid regions
3. Urban recharge method
4. Irrigated areas
5. EA/FAO method

The mechanisms required at each recharge node are chosen by specifying an integer id number in the appropriate position in the array contained in the file recharge.asc. The array in recharge.asc is independent of the grid structure defined in the file grid.dat. This independence enables areas of recharge mechanisms to be specified regardless of any grid refinement.

The general philosophy of the input files for ZOODRM is an array generated by ArcView containing integer id numbers. These id numbers provide links to the appropriate data files. For example the file soil.asc contains the areal distribution of soil types for the model and a file soil##.dat exists for each soil type. If, for example, there are four soil types required by the model, then the array within soil.asc will contain a distribution of the numbers 1 to 4. Combined with this data array will be four files named soil01.dat, soil02.dat, soil03.dat and soil04.dat. These files contain the data required at the locations in the array with the relevant integer id.

Table 1 List of all ZOOMDRM input files

Filename	Description
Spatial information files (Must exist)	
Aspect.asc	File that describes the direction of the ground surface at each element of the data array. (1 for East, 2 for North, 3 for West and 4 for South).
Geology.asc	File that gives the geology type at each element of the data array.
IrrigatedAreas.asc	File that allocates one reference number for irrigated areas, if they exist, at each element of the data array.
Recharge.asc	File that gives the recharge calculation type at each element of the data array. 1 for SMD calculation method, 2 for WT calculation method and 5 for FAO calculation method. To specify urban or irrigated areas recharge calculations the model uses automatically number 3 or 4. Do not use either number 3 or 4 in this file.
Soil.asc	File that gives the soil type at each element of the data array.
Topography.asc	File that gives the ground surface elevation at each element of the data array.
UnsatMap.asc	This file defines if the recharge value calculated at one Recharge node is passed to and memorised at the Unsaturated node beneath it.
UrbanAreas.asc	File allocates one reference number for urban areas, if they exist, at each element of the data array.
Spatial information files (Additional files)	
Plants.asc	File that gives the crop type at each element of the data array. The values of the data array are used if the majority landuse type is specified in plants.dat. This file with the data array must exist if SMD or FAO recharge calculation methods are used. (Need to specify explicitly that you are using these recharge calculation methods in Input.dat).
Climate information files	
Evapgrid.dat (Must exist)	File that allocates one reference number for a PE station at each element of the data array. It also gives the names, the record lengths and the evaporation long-term averages of the PE stations. This file gives a distribution of the evaporation long-term average over the gridded area.
Raingrid.dat (Must exist)	File required if rainfall is to be calculated from data recorded at rain stations. File that allocates one reference number for a rain station at each data node. It also gives the names, the record lengths and the rainfall long-term averages of the rain stations. This file gives a distribution of the rainfall long-term average over the gridded area.
yy.dd.mon.asc or yyyy.dd.mon.asc	The model automatically can read grids of daily rainfall directly if available. These files must be in ASCII format with the mentioned file name formats.

Detailed input files (Must exist if the related object is created)

CDValues##.dat	File that gives the C, D and the empirical factor values for each SMD crop object. One file for each object.
CropFAO##.dat	File that gives the characteristics of each crop object. One file for each object.
IrrigatedArea##.dat	File that gives the characteristics of each irrigated area object. One file for each object.
Spring##.dat	File that gives the characteristics of each spring object. One file for each object.
ROValue##.dat	File that gives the runoff and run on values for each soil type. One file for each soil type.
Soil##.dat	File that gives the characteristics of each soil type. One file for each soil type.
UrbanArea##.dat	File that gives the characteristics of each urban area object. One file for each object.
River##.dat	File that gives the characteristics of each river object. One file for each object.

Additional data files

A set of evaporation files.	Files holding the data recorded at the evaporation stations
A set of rainfall files.	Files holding the data recorded at the rainfall stations

Model input files (Must exist)

Clock.dat	File to set the start and end simulation times.
Grids.dat	File created by ZETUP (ZOOMQ3D) and read directly by the recharge model.
Input.dat	File needed to specify if the recharge node grid shapes are different from the unsaturated node grid shapes
Output.dat	File to set the required model output files.
Plants.dat	File to specify the crop types at the data nodes
Rechhydro.dat	File to specify the location where the variation of recharge with time is recorded.
Rivers.dat	File created by ZETUP (ZOOMQ3D) and read directly by the recharge model
BaseUnsatgrid.dat	File that must exist if the upper recharge grid is different from the lower unsaturated grid. ZETUP (ZOOMQ3D) can be used to create a data file representing the unsaturated grid ("Grids.dat" file must be renamed as "BaseUnsatgrid.dat" in this case).
Springdata.dat	File that gives the number of spring and specific information about each spring.
Aspect.dat	File that gives the locations of the nodes where a user defined aspect directions are set.

Table 2 ZOODRM input files which are relevant to model features

Model feature	Relevant file names	Relevant section
Grid structure	Grids.dat – structure of model grids, provided by ZETUP	4.2
Recharge calculation node type	Recharge.asc – sets recharge node type from 1 to 5	5.1
Unsaturated zone nodes	BaseUnsatgrid.dat – structure of unsaturated zone grids. Input.dat – matching groundwater and surface water catchments	4.2
Unsaturated grid with no calculation	UnsatMap.asc	4.2
Rainfall	Raingrid.dat – number of raingauges, theissen polygons, distribution of long-term average rainfall ###.### – daily rainfall for each raingauge	5.2
Potential Evaporation	Evapgrid.dat - number of evaporation stations, theissen polygons, distribution of long-term average PE ###.pe or ###.txt – monthly PE data	5.3
Soil moisture deficit calculation (recharge node id = 1)	Plants.asc – distribution of plant types Plants.dat – Number of crop types per node CDValues##.dat – monthly C and D values for each plant	5.4
Wetting threshold method (recharge node id = 2)	Soil.asc – distribution of soil types Soil##.dat – monthly values of ST	5.5
FAO recharge calculation (recharge node id = 5)	Plants.asc - distribution of plant types Plants.dat – Number of crop types per node CropFAO##.dat – Specific data for FAO method Soil.asc - distribution of soil types Soil##.dat - Specific data for FAO method	5.4; 5.6
Urbanised areas (recharge node id = 3)	Urbanareas.asc – Distribution of urban areas Urbanarea##.dat – Data for each urban area	5.6
Irrigated areas (recharge node id = 4)	Irrigatedareas.asc – Distribution of irrigated areas Irrigatedarea##.dat – Data for each irrigatedarea	5.6
Rivers	Rivers.dat – ZOOM/ZETUP file with structure of rivers Aspect.asc – aspect map for producing routing to rivers River##.dat – data for each river Geology.asc – distribution of geological outcrops for runoff, run on and river losses ROValue##.dat – runoff and run on values for each geology type	5.7
Springs	Topography.asc – land surface from DTM Springdata.dat – number and position of springs Spring##.dat – data for each spring	5.8
Time discretisation	Clock.dat – start and end time or model simulation Input.dat – stress period setup	5.9
Controlling data output	Output.dat – daily output on or off Rechhydro.dat – time series of recharge at any given point	5.9

4.2 RELATIONSHIP BETWEEN GROUNDWATER AND SURFACE WATER CATCHMENTS WITHIN THE MODEL

The recharge model ZOODRM is compatible with the groundwater flow model ZOOMQ3D (Jackson, 2001) in terms of the possibility of refining the numerical grids over selected areas and producing numerical recharge values at the nodes of the refined grids. ZOODRM reads two files produced by ZETUP program, a part of ZOOMQ3D, to build numerical grids that are identical to ZOOMQ3D grids. These files are grids.dat and rivers.dat. The file grids.dat contains the geometry and structure of the ZOOMQ3D model grids. Whereas the file rivers.dat contains the river geometry used for the ZOOMQ3D model. A description of the structure of these files and how they can be created is given in the ZETUP user's manual (Jackson and Spink, 2004).

It is likely that the areal extent of the surface water catchment could be different from the areal extent of the groundwater catchment. The recharge model has to model the surface water catchment in this case and yet produce results over selected nodes representing the groundwater catchment. It is possible to introduce simplifications in the recharge modelling approach so that the surface area outside the groundwater area is ignored and distributed recharge calculations are undertaken only over the groundwater catchment. However, the use of two levels of calculation grids in ZOODRM solves this problem by allowing a complete representation of the surface catchment while at the same time producing results over an area defined by the groundwater catchment. The recharge grid is the first calculation grid level in the recharge model. This grid can be made to fit the whole surface water catchment area while the second grid level, the unsaturated calculation grid, can be built so it represents the size and extent of the groundwater catchment. Any grid refinement, however, should fall within the groundwater catchment limits. If this approach is used, the two input files rivers.dat and grids.dat should be prepared using ZETUP and represent the whole surface water catchment. The grids.dat file used to build the groundwater model should be also available for the recharge model but renamed as BaseUnsatGrid.dat. This file will produce an unsaturated grid having a size similar to that of the groundwater model grid.

The ASCII file Recharge.asc, which is used to specify the type of recharge calculation method at a specified node, can be also used to control the creation of the recharge nodes. This file has to hold an id value of 1, 2 or 5 at the location of a node to allow the creation of a recharge node at this location, otherwise the existence of any other value will prevent a node being created. Another ASCII file, UnsatMap.asc is introduced in the model to control the creation of the unsaturated node. Before creating any new unsaturated node, the recharge model uses this file to check if an id number of 1 is specified at this location. If yes the node will be created otherwise the node creation is skipped.

Table 3 gives additional explanations about the different scenarios that can be dealt by the recharge model and the corresponding input files required.

Table 3 Description of files

Scenario	Description	Comment	Used Files	grids.dat and rivers.dat	BaseUnsatGrid.dat	Recharge.asc	UnsatMap.asc
1	Surface and groundwater catchments are the same.	Flag set to 'N' in input.dat	rivers.dat grids.dat UnsatMap.asc Recharge.asc	Prepared by ZETUP. Represent the surface catchment		Covers the whole recharge grid.	Covers the whole unsaturated grid.
2	Surface and groundwater catchments are different.	Flag set to 'Y' in input.dat	rivers.dat grids.dat BaseUnsatGrid.dat UnsatMap.asc Recharge.asc	Prepared by ZETUP. Represent the surface catchment	Prepared by ZETUP. Represent the groundwater catchment	Covers the whole recharge grid.	Covers the whole unsaturated grid.
3	Surface and groundwater catchments are the same. Part of the unsaturated grid is not required	Flag set to 'N' in input.dat	rivers.dat grids.dat UnsatMap.asc Recharge.asc	Prepared by ZETUP. Represent the surface catchment		Covers the whole recharge grid.	Covers parts of the unsaturated grid.
4	Surface and groundwater catchments are the same. Part of the recharge grid is not required	Flag set to 'N' in input.dat	rivers.dat grids.dat UnsatMap.asc Recharge.asc	Prepared by ZETUP. Represent the surface catchment		Covers parts of the recharge grid.	Identical to Recharge.asc
5	Surface and groundwater catchments are different. Part of the unsaturated grid is not required	Flag set to 'Y' in input.dat	rivers.dat grids.dat BaseUnsatGrid.dat UnsatMap.asc Recharge.asc	Prepared by ZETUP. Represent the surface catchment	Prepared by ZETUP. Represent the groundwater catchment	Covers the whole recharge grid.	Covers the whole unsaturated grid.
6	Surface and groundwater catchments are different. Part of the recharge grid is not required	Flag set to 'Y' in input.dat	rivers.dat grids.dat BaseUnsatGrid.dat UnsatMap.asc Recharge.asc	Prepared by ZETUP. Represent the surface catchment	Prepared by ZETUP. Represent the groundwater catchment	Covers the whole recharge grid.	Covers the whole unsaturated grid.

5 Detailed description of input files

5.1 SPATIAL INFORMATION FILES

The first set of input files are data files prepared in ArcView or ArcGIS (ESRI) and exported in ASCII Raster format. These files represent the spatial characteristics of the study area. They include its topographical, geological and landuse characteristics. The area information is gridded to the required resolution and then exported in the required (.asc) ASCII format file. The areal extent of these files should be larger than the extent of the recharge model area (Figure 8). The parts that are outside the boundary of the recharge model are ignored and the model will produce an error message if a model node is outside the data file coverage.

If no grid refinement is considered, it is preferable that these files are gridded in the ArcGIS environment using a cell size equal to the one used in the recharge model. Using a cell size in the gridded data files that is larger or finer than the model cell size introduces errors and reduces the accuracy of the produced results. This is caused by the information being extracted from the input files based on the values of the co-ordinates of a single point instead of the size of the area of this cell. When refinement is included, the error introduced by gridding the spatial data cannot be avoided; it is advised that data are gridded based on a cell size equal to the size of the cell located on the finer mesh.

A list of the required data files is given in Table 4. All these files have to exist for the model to run even in the case when no irrigated or urban areas are considered in the study. IrrigatedAreas.asc and UrbanAreas.asc in this case represent a certain areal extent that covers the study area but all the values in the array will be zero.

An example of the ASCII ArcGIS exported files is presented in Table 5.

Table 4 List of data files giving the spatial information of the study area.

Aspect.asc
Geology.asc
IrrigatedAreas.asc
Plants.asc
Recharge.asc
Soil.asc
Topography.asc
UnsatMap.asc
UrbanAreas.asc

Table 5 **Details of an ArcGIS exported file in ASCII format.**

ncols	577	Number of columns in the array
nrows	503	Number of rows in the array
xllcorner	285405.072581	Lower left corner of the gridded area
yllcorner	562693.194889	Upper left corner of the gridded area
cellsize	50	Cell size
NODATA_value	-9999	If -9999 is shown in the array of data, no information is found at the node location while gridding.
		An array of data showing nodal codes.
1 1 1 1 2 2 2 2 2 2 2 2 1 1 1 1 1		
1 1 1 1 2 2 2 2 2 2 2 2 1 1 1 1 1		
1 1 1 1 2 2 2 2 2 2 2 2 1 1 1 1 1		
1 1 1 1 2 2 2 2 2 2 2 2 3 3 3 3 3		
1 1 1 2 2 2 2 2 2 2 3 3 3 3 3 3		
1 1 2 2 2 2 2 3 3 3 3 3 3 3 3 3		
2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 3		
.		
.		

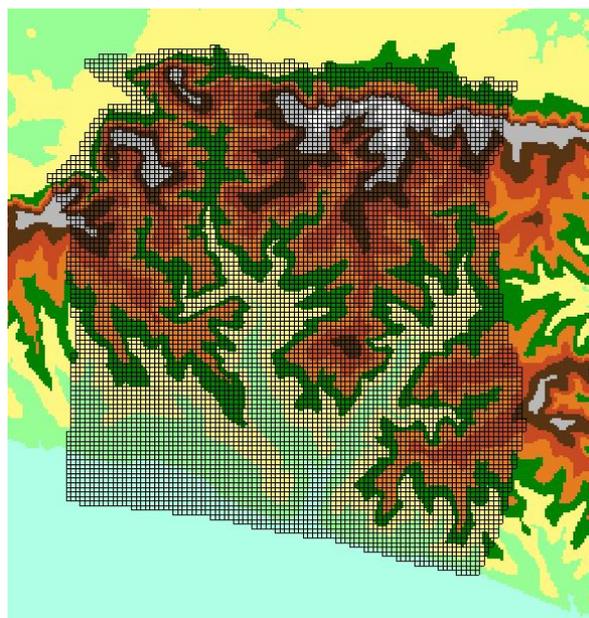
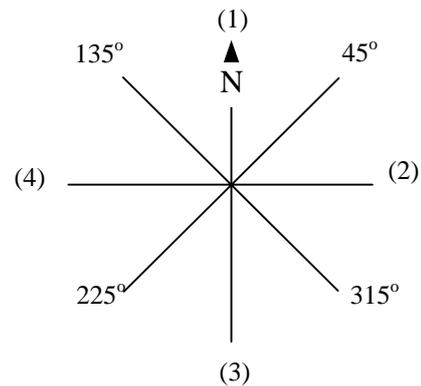


Figure 8 Illustration of a gridded data set extending outside the boundary of the recharge model grid

5.1.1 The aspect file “Aspect.asc”

This file describes the direction of the ground surface at each element of the data array used in surface water routing to rivers (Section 2.2.6). The model accepts only four directions. The values of the data array must, therefore, be integer values ranging from 1 to 4. A value of 1 indicates a ground surface inclination towards the North, while the values 2, 3 and 4 indicates ground surface inclination towards the East, South and West respectively. If this file is generated from a Digital Terrain Model (DTM) in an ArcView environment you need to reclassify the generated data as follows:

Old values (Degrees)	New values
315 – 360, 0 – 45	1
45 – 135	2
135 – 225	3
225 – 315	4



5.1.2 The geology file “Geology.asc”

The values of the data array of this file are integers representing the IDs of the geology types. The geology type affects the amount of water lost from the River nodes to the Unsaturated nodes (Section 5.7.2) and the connections between the Unsaturated nodes and Spring nodes (Section 5.8). At least one geology type must be defined.

5.1.3 The irrigated areas file “IrrigatedAreas.asc”

The values of the data array are integers representing the IDs of the irrigated areas with an ID of zero indicating the absence of irrigation at the location defined by the array element. For each irrigated area there should be a corresponding data file called “IrrigatedArea##.dat” that gives its characteristics (Section 5.6.5). Even if irrigated areas do not exist in the modelled area the data array of the ASCII file must exist and hold values of zero.

5.1.4 The plants file “Plants.asc”

This file defines the crop type at each element of the data array. The values of the data array are used if the majority landuse type is specified in plants.dat (the first value is set to zero in plants.dat). This grid file must exist if the SMD or FAO recharge calculation methods are used (Sections 2.2.1 and 2.2.3). (The user needs to specify explicitly in input.dat (Section 5.9.2) which of these recharge calculation methods is used). If percentage landuse type is used (the first value of plants.dat is set to one (Section 5.4)), the data array is not used; however, it must exist (set values to zero).

5.1.5 The recharge file “Recharge.asc”

The values of the data array are integers specifying the application of the Soil Moisture Deficit (SMD) calculation method (value of 1), the Wetting Threshold calculation method (value of 2), or the FAO calculation method (value of 5). Integers 3 and 4 relate to irrigated

and urban areas respectively but should not be entered in this array. Refer to Sections 2.2.1, 2.2.2, 2.2.3, 2.2.4 and 2.2.5 for the descriptions of the different methods.

5.1.6 The soil file “Soil.asc”

The values of the data array of this file are integers representing the IDs of the soil types. This file relates to the application of the (Wetting Threshold) WT and FAO recharge calculation method. For each soil type there must be a complementing data file “Soil##.asc” giving the wetting threshold value and other soil characteristics (Section 5.5). Even if the SMD calculation method is used this file must exist and the values of the elements of the data array must be set to zero.

5.1.7 The topography file “Topography.asc”

This file gives the ground surface elevation at each element of the grid. This file is used for setting up the link between the spring nodes and the unsaturated nodes (Section 2.2.7); however, it must exist even if springs are not considered.

5.1.8 The unsaturated map file “UnsatMap.asc”

This file defines if the recharge value calculated at one recharge node is passed to and stored at the unsaturated node beneath it (Section 2.2). The values contained in the data array must be either 0 or 1. An Unsaturated node is created if the value returned from this file is equal to one. If the unsaturated zone node is not created, the recharge calculated at the recharge node above will be discarded.

5.1.9 The urban areas file “UrbanAreas.asc”

The values of the data array are integers representing the IDs of the urban areas. An ID of zero indicates the absence of urbanisation at the location defined by the array element. For each urban area there should be a complementing data file called “UrbanArea##.dat” that gives its characteristics (Section 5.6.4). Even if urban areas do not exist in the study area the data array of the ASCII file must exist and hold values of zero.

5.1.10 The runoff/run-on file “Runoff.asc”

The values of the data array of this file are integers representing the IDs of different zone types. For each zone runoff and run on coefficients are specified in files named “ROValues##.dat” (Section 5.7). If there are N zones, a set of N files named “ROValuesN.dat” must exist where N is a two-digit integer (01 to 99). At least one runoff/run-on zone type must be defined.

5.2 RAINFALL

There are two options to set the rainfall conditions of the study area. This is by either reading rainfall data at specified rain gauges and distributing them using the Thiessen polygons or by preparing the distributed rainfall outside the recharge model environment, writing them into files and allowing the recharge model to read these files. In the first case, Raingrid.dat data file is used; however, in the second case both Raingrid.dat and either ##.##.mon.asc or #####.##.mon.asc data files are used. Where ##.##.mon.asc and #####.##.mon.asc are ASCII data files and the # represents a number. The ##.## and #####.## of the first and second file types give the year followed by the day of the considered date in the format yy.dd and yyyy.dd (year.day) respectively.

By default, the model will assume that the daily rainfall is calculated using the rain gauge data and Thiessen polygons and opens Raingrid.dat. A line by line explanation of this file is given in Table 6. If the number of raingauges is set to zero, the model switches to determining the rain information from the ASCII files. For a given date, the model searches for either ###.mon.asc or ####.###.mon.asc and reads the one that exists. If both files exist, ###.mon.asc is considered. ###.mon.asc and ####.###.mon.asc input files have the format of the file shown in Table 5.

Table 6 **Details for file Raingrid.dat.**

1000 1000	Mesh spacing in the X direction (Δx)
	Mesh spacing in the Y direction (Δy)
27 25	Number of columns of the data array
	Number of rows of the data array
287000. 588000.	X followed by the Y co-ordinates of the lower left corner.
6	Number of rainfall station data to be read
1 1 1139 1 1961 12 2001 Blackwood.prn	For each line: Rainfall station id, Substitute station id, LTA rainfall, Start month Start year, End month End year, Name of file to be read
2 1 1042 1 1961 11 1998 CrichtonRoyal.prn	
3 1 1191 1 1961 2 2001 LochruttonWWks.prn	
.....	
1	Grid of distribution of Thiessen polygon
1	
6 6 6 6 6 6 6 6 6 2 2 2 2 2 2 2 2 2 2 2	
6 6 6 6 6 6 6 6 2 2 2 2 2 2 2 2 2 2 2 2	
.....	
.	
1	Default substitute raingauge station.
LTAFactor	“LTAFactor”
1.0	Multiplier for LTA values. This factor multiplies the LTA values given in the block of data given next to produce the actual value of LTA rainfall.
1257 1231 1201 1146 1145 1153 1195 1185	Grid of distribution of LTA values
1275 1257 1221 1207 1178 1128 1112 1107	

The rainfall files may take any name with any extension; however, the recharge model is set to read one format of these files. This is by reading the daily rainfall record line by line as explained by the rainfall file shown in Table 7. Note that the list of data must terminate by (-1 -1 -1).

Table 7 Explanation of the rainfall files giving the rainfall values at one rainfall station.

Glencaple				Comment line giving the name of the rainfall station
1970	1	1	0.00	Rainfall values at the considered times. (Year Month Day Value)
1970	1	2	0.00	
1970	1	3	0.40	Time should be within the time interval specified in "Raingrid.dat" input file
1970	1	4	0.00	
1970	1	5	2.90	
1970	1	6	0.00	
1970	1	7	0.00	
1970	1	8	6.00	
1970	1	9	26.10	
1970	1	10	0.90	
1970	1	11	12.70	
1970	1	12	4.60	
1970	1	13	0.50	
1970	1	14	3.50	
:				
:				
:				
-1	-1	-1		

The following approach is used by the model to distribute the rainfall data and applies for the inclusion of the evaporation data. Rainfall is measured as a sequence of daily totals (monthly in case of evaporation), which depending on the location of the raingauge, has a unique pattern of daily measurements and different long-term averages. The time series and totals of the rainfall are influenced by a number of factors, including topography, direction of prevailing wind, etc. To provide a distribution of rainfall, an area associated with each raingauge is first defined. This area can be used with the gridded LTA rainfall to enable the rainfall measured at a raingauge to be interpolated to any point within the area of influence of that raingauge. Rainfall is then calculated by multiplying the rainfall at the raingauge by the ratio of the LTA at the point in space to the LTA of the raingauge.

$$Rf = (Rf_{LTA}/Rf_{RGLTA}) \times Rf_{RG}$$

Where:

Rf – Rainfall at required location

Rf_{RG} – Rainfall at raingauge

Rf_{LTA} – Long term average rainfall at required location

Rf_{RG LTA} – Long term average rainfall at raingauge

The ideal would be a continuous daily rainfall record from the start of the model run to the end. However, some of the raingauges have significantly shorter record lengths, but have to be used to provide the best possible geographical coverage of rainfall data. To ensure a continuous distribution of rainfall, when data do not exist, then a substitute raingauge is used. This is specified in the input file to the model. Raingauges with short record lengths, revert to a substitute raingauge. If this raingauge has no data, then a default raingauge is used.

The evaporation files should have the “.pe” or the “.txt” extension. The reason for this is that the recharge model can read the evaporation information as a monthly time series or as a repeated pattern of monthly averages. If the evaporation file has a “.txt” extension, the recharge model assumes a monthly evaporation input data and reads from a file having the format shown in Table 9. If the evaporation file has a “.pe” extension, the recharge model assumes a average monthly evaporation input data and reads from a file with the format shown in Table 10.

Table 9 Explanation of the evaporation file with extension “.txt” giving the evaporation values at one evaporation station.

YEAR	MONTH	PE	Comment line	
1970	4	48.5	Evaporation values at the considered months of the considered years. (Year Month Value)	
1970	5	79		
1970	6	94		
1970	7	79.1		Time should be within the time interval specified in “Evapgrid.dat” input file
1970	8	71.9		
1970	9	47.2		
1970	10	33.2		
1970	11	19.3		
1970	12	12.2		
1971	1	11.7		
1971	2	10.5		
1971	3	17.5		
1971	4	32.9		
1971	5	10.5		
1971	6	17.5		
:				
:				
:				

Table 10 Explanation of the evaporation files with extension “.pe” giving the evaporation values at one evaporation station.

Glencaple		Comment line giving the name of the evaporation station
Jan	70.5	Evaporation values at each month of one typical year
Feb	66.6	
Mar	85.1	
Apr	154.3	
May	182.9	
Jun	240.6	
Jul	289.7	
Aug	224.5	
Sep	182.0	
Oct	127.7	
Nov	143.0	
Dec	83.6	

5.4 PLANTS

“Plants.dat” input file gives information about the crops considered in the area and the percentage of the area each crop occupies at one location. The file starts with a flag that tells the model to use a majority plant type or to use the percentage plant type in case more than one plant type exists at one location. The number of plants that require the use of the conventional SMD recharge calculation method is then set followed by the number of plants/crops that require the application of the FAO recharge calculation method. Blocks of data follow these lines. The blocks of data are used if the calculation method flag is set to 1, i.e. several plant types are considered at one node of the model. If the calculation method flag is set to 0, i.e. each model node has only one plant type, these blocks of data can be ignored. Plants.asc file defines the plant type at each model node when the calculation method flag is set to zero.

The values presented in the blocks of data give the percentage each crop occupies at the considered location. The number of blocks is equal to the sum of the numbers of the two crop types and if there are n SMD crops, the n+1 block of data corresponds to the first FAO crop. This file is detailed in Table 11. It should be noted that at a location where the SMD recharge calculation is applied, the sum of numbers given by the SMD blocks should be equal to 100 at this location. The numbers in the FAO blocks should be zeros at the considered locations.

Table 11 **Details for file Plants.dat.**

0	<p>Calculation method flag:</p> <ul style="list-style-type: none"> - If 0 the majority crop type is applied, i.e. only one crop type is allocated to each recharge node. - If 1 the percentage crop type is applied, each recharge node may be allocated more than one crop type.
2	<p>Total number of crops in the area where the SMD recharge calculation method is applied.</p>
5	<p>Total number of crops in the area where the FAO recharge calculation method is applied.</p>
PercentageLanduse 1	<p>A block of data always preceded by one comment line.</p>
0 0 0 0 0 0 0 0.....	<ul style="list-style-type: none"> - The data array should have the same size as the array given in the file "Plants.asc".
0 0 0 0 0 0 0 0.....	<ul style="list-style-type: none"> - The data array gives the percentage of crop type at each node.
0 0 0 0 0 10 10 15 15 15 15.....	<ul style="list-style-type: none"> - There should be a number of data blocks that is equal to the sum of the number of SMD and FAO crops.
etc.	<ul style="list-style-type: none"> - The sum of values extracted from all blocks at one location should total to 100.
PercentageLanduse 2	<ul style="list-style-type: none"> - If there are more than one crop type and one block of data shows 100% of one crop at one location, the other blocks should show zero at that location
0 0 0 0 0 0 0 0.....	<ul style="list-style-type: none"> - The first block of data corresponds to the first SMD crop type unless there are zero SMD crops
0 0 0 0 0 45 20 30 60.....	<ul style="list-style-type: none"> - If there are n SMD crops, the n+1 block of data corresponds to the first FAO crop.
0 0 0 0 0 10 10 15 15 15 15.....	
etc.	
PercentageLanduse 3	
0 0 0 0 0 0 0 0.....	
0 0 0 0 0 45 20 30 60.....	
0 0 0 0 0 10 10 15 15 15 15.....	
etc.	

5.5 SOIL

“Soil##.dat” input file gives the characteristics of the considered soil type. This file is related to “Soil.asc” and gives the monthly variations of the soil threshold of the considered soil type, information used by the application of the wetting threshold calculation method. It also gives other characteristics such as the soil moisture contents at the field capacity at the wilting point, and the depletion factor. The latter information is used in the application of the FAO recharge calculation method. The input data of this file are explained in Table 12.

Table 12 **Details for file Soil##.dat.**

15.0	Monthly wetting threshold values.
15.0	
15.0	
15.0	
15.0	
15.0	
15.0	
15.0	
15.0	
15.0	
15.0	
Moisture content at field capacity	Comment line
0.41	Value of the soil moisture content at field capacity
Permanent wilting point	Comment line
0.24	Value of the soil moisture content at wilting point
Depletion factor	Comment line
0.39	Depletion factor

5.6 RECHARGE CALCULATION METHOD

5.6.1 Soil moisture deficit method

The “CDValues##.dat” input file is required if a crop type, to which the conventional SMD recharge method applies, is considered in the model. This file gives the monthly values of the root constant (C) and the wilting point (D) of the crop and the relationship between the actual evaporation and the potential evaporation when the soil moisture deficit value is located between C and D. This file is detailed in Table 13.

The number of the file is related to the id in the data array found in plants.asc (see Section 5.4)

Table 13 Details for file CDValues##.dat.

0.1		Relationship between AE and PE when SMD is between C and D
30.0	75.0	Root constant (C) and Wilting Point (D) for each month
30.0	75.0	
30.0	75.0	
30.0	75.0	
30.0	75.0	
30.0	75.0	
30.0	75.0	
30.0	75.0	
30.0	75.0	
30.0	75.0	
30.0	75.0	
30.0	75.0	
30.0	75.0	
30.0	75.0	

5.6.2 Wetting threshold method

This information is held within the soils object (see Section 5.5).

5.6.3 Environment Agency FAO method

The “CropFAO##.dat” input file is required if a crop type, to which the FAO recharge calculation method applies, is considered in the model. This file gives the characteristics of the crop as explained in Table 14.

The number of the file is related to the id in the data array found in plants.asc (see Section 5.4)

Table 14 Details for file CropFAO##.dat.

Number of crop harvests per year	Comment line
1	Number of times the crop is harvested per year.
Initial crop coefficient	Comment line
1.15	Initial crop coefficient
Mid crop coefficient	Comment line
0.95	Mid crop coefficient
End crop coefficient	Comment line
0.85	End crop coefficient
Minimum root depth (m)	Comment line
1.0	Minimum root depth
Maximum root depth (m)	Comment line
1.0	Maximum root depth
Depletion factor	Comment line
0.7	Depletion factor
Minimum percentage cover	Comment line
100.	Minimum percentage cover
Maximum percentage cover	Comment line
100.	Maximum percentage cover
Season 1	Block of information repeated for each harvest season in one year.
Harvest month	
10	The Harvest time, the typical drilling time, the emergence period, time when crop covers 100% of the area and time when senescence begins are given here.
Typical drilling month	
11	
Emergence month	
3	
100% crop cover month	
5	The difference between the harvest time of the first season and the time when senescence begins of the last season should not exceed 12 months.
Senescence begins month	
9	

5.6.4 Urban recharge

The “UrbanArea##.dat” input file is required if urban areas exist in the study area. This file gives the characteristics of the urban area, such as the daily flow supplied to the urban area, the losses from the pressurised water mains and sewers, the percentage of the impermeable area, etc. The input data are explained in Table 15.

Table 15 **Details for file UrbanArea##.dat.**

Flow in PWM (m ³ /d)	Comment line
12055	Total flow supplied for the urban area
Losses from PWM	Comment line
0.3	Percentage loss from the pressurised water mains
Flow in sewers (m ³ /d)	Comment line
12055	Total flow in all sewers
Losses from sewers	Comment line
0.15	Percentage loss from the pressurised water mains
Impermeable area	Comment line
0.8	Percentage of the impermeable area
Runoff coefficient - Impermeable area	Comment line
0.9	Runoff coefficient for the impermeable part of the area
Runoff coefficient - Grass area	Comment line
0.4	Runoff coefficient for the grass part of the area
Grass C value	Comment line
0.3	The root constant (C) value for the grass area
Grass D value	Comment line
0.6	The wilting point (D) value for the grass area
Empirical constant	Comment line
0.1	Relationship between AE and PE when SMD is between C and D
Position of river node, X-Coord. and Y-coord	Comment line
151877 192057	The X and Y co-ordinates of the river node at which the sewers of the urban area discharges

5.6.5 Irrigated area losses

The “IrrigatedArea##.dat” input file is required if irrigated areas exist in the study area. This file gives the characteristics of the irrigated area, such as the number of irrigation months and the quantity of the supplied water in each month, the transmission and field losses and the characteristics of the crop cultivated in this area. The input data are explained in Table 16.

Table 16 Details for file IrrigatedArea##.dat.

Number of irrigated months	Comment line
7	Number of month when areas are irrigated
Irrigation months	Comment line
4 5 6 7 8 9 10	The months when irrigation is applied
Supplied irrigation per month (MCM/month)	Comment line
0.38 0.77 1.15 1.15 1.15 0.77 0.38	Irrigation supplied in each month
Transmission losses	Comment line
0.15	Losses caused by sewer leakages
Field losses	Comment line
0.25	Losses caused by water leaving the soil
Runoff coefficient - Grass area	Comment line
0.6	Runoff coefficient for the grass part of the area
Grass C value	Comment line
0.3	The root constant (C) value for the grass area
Grass D value	Comment line
0.6	The wilting point (D) value for the grass area
Empirical constant	Comment line
0.1	Relationship between AE and PE when SMD is between C and D

5.7 RUNOFF TO SURFACE WATER FEATURES

5.7.1 Runoff coefficients

Since at least one geology type is considered in the study area, at least one “ROValues##.dat” file should be available for the recharge model. This file is related to “Geology.asc” and gives the monthly variations of the runoff and the run on coefficients of the considered geology type. Please note that the product of the run on coefficient and the maximum cell length of the model must be less than one. The input data of this file are explained in Table 17.

Table 17 Details for file ROValues##.dat.

0.10	0.00002	Runoff coefficient (Dimensionless) followed by the Run on Coefficient (m ⁻¹) for each month.
0.10	0.00002	
0.10	0.00002	
0.10	0.00002	
0.10	0.00002	
0.10	0.00002	
0.10	0.00002	
0.10	0.00002	
0.10	0.00002	
0.10	0.00002	
0.10	0.00002	
0.10	0.00002	
0.10	0.00002	

5.7.2 Rivers

“River##.dat” input file gives the information required by the River object to know the gauging location and the time when river flows are recorded by the model. The input data of this file are explained in Table 18.

Table 18 Details for file River##.dat.

Number of gauging stations	Comment line
2	Total number of gauging stations where river flow will be recorded (There should be at least one gauging station)
X and Y of gauging station nodes	Comment line
297500.0 571500.0	The X and Y co-ordinates of the gauging stations
287500.0 576500.0	
Number of days at which to record river flows	Comment line
1	The number of days at which you want to produce script files showing the flows at all river nodes
Date to write river flows (Day ##, Month ##, Year #####)	Comment line
31 01 1991	The dates of the above mentioned days. Dates format is DD MM YYYY
Number of river loss types	Comment line
3	The number of river loss coefficients. This is usually the number of geology types but it could be different. However, it is safer to set this number to the number of geology types.
River loss corresponding to each GeoCode	Two comment lines
Geocode	RiverLoss
10	0.01
11	0.01
12	0.01
	The river loss coefficient for each geology type the river may run over.
	The geology types that the river nodes may have should be covered here. So a river may have three related geology types and these could geology types 10, 11 and 12.
	10, 11 and 12 should be mentioned in this case with the associated loss coefficient.

5.8 SPRINGS

“SpringData.dat” input file is required to create the spring objects. It gives the number of springs, their co-ordinates and ground elevations and the co-ordinates of the stream nodes to which they discharge their flows. The structure of this file is explained in Table 19.

Table 19 Details for file SpringData.dat.

Number of Springs	Comment line
3	Total number of springs
Coordinates (X, Y, Z), MaxDistance NbrLinkedGeology Related stream node(X, Y)	Comment line
298000. 580000. 10. 5000 2 300500 575500	Each line gives information about one spring. These are:
159000. 155000. 324. 5000 3 159000 155050	- the coordinates of the spring (X, Y and Z)
.....	- the radius of the area encircling the spring and where recharge nodes can be connected to the spring
	- the number of geology types that the spring can connect to
	- the co-ordinates (X and Y) of the stream node where the spring discharges.

“Spring##.dat” input file gives the information required by each Spring object to connect to the recharge nodes. This file is required in conjunction with the “SpringData.dat” input file. The input data of this file are explained in Table 20.

Table 20 Details for file Spring##.dat.

Related Hydraulic conductivity (m/d)	Comment line
5	The hydraulic conductivity used to calculate the daily flow at this Spring object
Linked geology types	Comment line

5	The recharge nodes that are associated with geology type stated here will be connected to this Spring object
1	
2	The number of geology types is given in the input data file "SpringData.dat"
.	
.	
.	

5.9 OTHER INPUT FILES

5.9.1 Start and end time of model

File "Clock.dat" gives the start and the end time for the model simulation in day, month and year as explained in Table 21.

Table 21 Details for file Clock.dat.

1	1	1970	Simulation start time (Day Month Year)
1	1	1972	Simulation stop time (Day Month Year)

5.9.2 Input control file

File "Input.dat" is used to set two flags one to specify the use of the SMD or FAO calculation methods and the second to indicate that the recharge grid is different from the unsaturated grid. In addition, this file control the time at which the recharge results are produced. There are two options. The first is to produce the results at the end of a stress period equivalent to a corresponding month. The second is to produce the results at the end of stress periods the lengths of which are user defined. In the second option, the user has to specify the number of stress periods per block. If the length of simulation time is greater than the block length, the stress periods will be repeated from the beginning as defined by the user. Table 22 shows the structure of this file.

Table 22 Details for file Input.dat.

Are you using the SMD or FAO recharge calculation method? (Y for yes and N for no. If Y needs include plants.dat and plants.asc)	Comment line
Y	Capital "Y" if the SMD or FAO recharge calculation methods are used. If "Y" include plants.dat and plants.asc data files.
Is Unsaturated grid different from the recharge grid? (Y for yes and N for no)	Comment line

Y	Capital “Y” if the base unsaturated node grid is different from the base recharge node grid. Capital “N” if not.
Use user defined stress periods	Comment line
Y	Capital “Y” if user defined stress periods are used and capital “N” if monthly stress periods are used.
Number of stress periods per block	Comment line that must exist even if no stress periods are used.
5	Number of stress periods per block. Line that must exist even if no stress periods are used.
Stress period lengths (Multiple of days)	Comment line that must exist even if no stress periods are used.
73 73 73 73 73	Number of days in each stress period. The recharge values will be produced at the end of each stress period. Line that must exist even if no stress periods are used.
Is the runoff coefficient related to the rainfall intensity and SMD level?	Comment line
1	“1” if yes and “0” if no.
Force aspect direction?	Comment line
Y	“Y” if yes and “N” if no

5.9.3 Output control file

Because of the large size of the output file that can be produced by the model, “Output.dat” file is introduced to allow the production of some of the output files to be user defined. The number and the coordinates of the nodes where the daily SMD variations are recorded and produced as time series are set in this file. In Version 1.03 of the model gridded recharge values can be produced during a defined period of the simulation. Two lines are added to “Output.dat” to specify this period of time. Table 23 shows the structure of this file.

Table 23 Details for file Output.dat.

Write Daily River Flow? (Y for yes)	Comment line
N	Capital “Y” to write daily flow, capital “N” if not.
Record Daily Flow At Gauging Stations? (Y for yes)	Comment line

Y	Capital “Y” to write daily flow, capital “N” if not.
Number of locations where daily SMD time series are produced	Comment line
2	Number of locations where daily SMD time series are produced
X and Y coordinates of nodes where SMD time series are produced	Comment line
150000 110000	The co-ordinates (X then Y) of the nodes where SMD time series are produced
175000 112500	
Start time for daily gridded recharge output (day month year)	Comment line
13 4 1972	Day Month Year
End time for daily gridded recharge output (Day month year)	Comment line
13 4 1982	Day Month Year

5.9.4 Recharge time series at a point

“Rechhydro.dat” input file is required to specify the locations where the recharge time series are recorded by the recharge model and written to the corresponding files. Table 24 gives the structure of this file.

Table 24 Details for file Rechhydro.dat.

3	Total number of nodes where the recharge time-series are recorded by the model
296000 581600	The co-ordinates (X then Y) of the nodes where the recharge time-series are recorded.
294990 578850	
296670 574320	

5.9.5 Aspect file Aspect.dat

The aspect directions at selected can be changed using an input file named “aspect.dat”. The first line of this line specifies the number of nodes at which aspect directions are specified. The locations of the nodes (the X Y co-ordinates) and the aspect directions (an integer from 1 to 4 where 1 indicates North, 2 indicates East, 3 indicates South and 4 indicates West.) are then listed. Table 25 gives the structure of this file.

Table 25 **Details for file Aspect.dat.**

4	Total number of nodes where the aspect directions are user specified.
460375 179350 1	A list of the co-ordinates (X then Y) of the node followed by and the aspect direction.
460375 179375 2	
460375 179400 3	
460250 179600 4	

PART 3 – Model output

6 Summary of output files produced by ZOODRM

6.1 THE PHILOSOPHY OF MODEL OUPUT

The philosophy behind the structure of ZOODRM model output is to separate different types of data between files. That is, each file contains one specific type of information only. This simplifies the post-processing of model output and means that standard software packages can be used to interpret and visualise results. All the output files have a very simple format and are easily examined using a text editor or processed using spreadsheet software.

The recharge model calculates recharge on a daily basis. However, regional groundwater flow models use stress periods that stretch over days or months and over which an average constant recharge values are applied. A daily output of the recharge values is not needed in this case and the output from the recharge model can be produced in accordance with the used stress periods to reduce the size of the output files. ZOOMQ3D also allows the use of stress periods that are smaller than one day. However, the availability of field data such as rainfall and evaporation data on a daily basis prevents the reduction of the stress period in the recharge model to less than one day. This is the only case when the recharge model ZOODRM cannot be compatible with ZOOMQ3D. Three types of output file are produced by the recharge model:

1. Output files that give the calculated recharge values.
2. Output files that give the time series results at given locations in the study area, at the rivers and at the springs.
3. DXF and AutoCAD script files for plotting the constructed grids, rivers and other features and checking the connections between these features.

Input files with extension “.asc” and some other input files are reproduced by the model. The new files hold the same names of the original files but have extensions of “.mir”. Table 26 shows a list of the output files produced by ZOODRM. These files are separated in this table based on their type or based on the feature they represent.

Table 26 Output files produced by ZOODRM

Model feature	Output file type	Relevant file names
Unsaturated nodes	Recharge results	Rech.out
		Rech.ts
		Rech.tv
		dailyrech.tv
		Script files
Recharge nodes	Water balance	UnsatToRech##.scr
		UnsatToSpring##.scr
	AutoCAD script files	DailyWBGrid.out
		LinkBR##.scr
		LinkTL##.scr
	DXF files	RoutingGrid##.scr
		RechGridBR##.dxf
		RechGridTL##.dxf
		Routing##.dxf
		Model results
Rivers	Model results	FlowRiver##.out
		GaugingRiver##.out
	Script files	DSLlink##.scr
		USLink.scr
		SpringToRiver##.scr
Springs	Model results	FlowAtSpring##.out
Ponds	Model results	pond##.out
	Script files	PondGrid##.scr

6.2 RECHARGE RESULTS

The calculated recharge values are written to three of output files. These are:

1. Main output file – rech.out
2. Monthly recharge file – rech.tv
3. Daily recharge file – dailyrech.tv
4. Monthly time series at the required locations as specified in rechydro.dat – rech.ts

The main output file (rech.out) contains the following information:

- Echoing grid setup
- Monthly recharge for each grid for both unlagged recharge and lagged (if possible) recharge

- Summaries of monthly recharge for each class of geological characteristics as specified in geology.asc
- LTA recharge for each grid as arrays and xyz format

The model produces monthly recharge values or values at the end of the stress period and writes them to rech.tv. Finally, monthly time series at the required locations as specified in rechydro.dat – rech.ts

6.2.1 River flow gauging

The river nodes of each river over which the river flow is monitored are specified in the input file of the river ‘River##.dat’. The daily recorded flows at these nodes are written to one file corresponding to the considered river. This file is called ‘GaugingRiver##.out’ where ## represents the river number for example 01. The output file contains one line of data for each day with the following format:

```
Day      Month      Year      Q1      Q2      . . . . . Qn
```

where

Day Month Year represent the date at the end of the day when flow is recorded

Q₁ is the flow (MI day⁻¹) cumulated at the first river node in one day

Q₂ is the flow (MI day⁻¹) cumulated at the second river node in one day

Q_n is the flow (MI day⁻¹) cumulated at the nth river node in one day

6.2.2 River flow accretion profiles

River flow accretion data are written to the output file ‘FlowRiver##.out’ where ## represents the spring number for example 01. The river flows cumulated at each river node are produced on a daily basis. To allow an easy plot of the produced results, the file gives flow results (MI day⁻¹) at nodes grouped based on the stream number they represent. The distance between the considered node and its adjacent upstream one is also given for this reason. The output file gives the stream number first, followed by the date when the results are recorded, followed by a comment line describing the numbers produced on the subsequent lines. This format is explained next:

```
Stream Number: 1
1/1/1970
X          Y          Reach      Flow
293000    575500    0.0        0.2
293500    576000    707.107    0.55
. . . . .
. . . . .
Stream Number: 2
1/1/1970
X          Y          Reach      Flow
292000    578000    0.0        0.1
292500    578000    500        1.03
```

.
.

where

X Y are the x and y coordinates of the river node

Reach is the distance between the considered node and its upstream one

Flow is the cumulative flow recorded at the river node.

6.2.3 Spring flows

Spring flows are written to the output file 'FlowAtSpring##.out' where ## represents the river number for example 01. The produced file gives the time elapsed in days from the start of the simulation and the corresponding flow in mm day^{-1} . The unsaturated zone water produced at one location may reach the spring at a time later than the end of the simulation. The produced file gives the spring flows recorded from the start of the simulation to the times when the considered spring stops receiving water. Care should be taken here since the spring flows recorded after the simulation stop time could be erroneous since no recharge is taken into consideration at these times.

6.2.4 Water balance

The different calculation water components are written to an output file named 'DailyWBGrid.out' on a daily basis. This file aims for checking the water balance and has the following format:

Date	Rainfall	Evaporation	Runoff	Run_on	Recovered water
	Recharge	Water balance			

where

Date is the date when the water components are recorded

Rainfall is the total rainfall value calculated at all recharge nodes of all recharge grids (mm)

Evaporation is the total evaporation value calculated at all recharge nodes of all recharge grids (mm)

Runoff is the total runoff value calculated at all recharge nodes of all recharge grids (mm)

Run_on is the total run on value calculated at all recharge nodes of all recharge grids (mm). This value is used to calculate the water balance of the following day

Recovered water is the total water recovered from the soil calculated at all recharge nodes of all recharge grids (mm)

Recharge is the total recharge value calculated at all recharge nodes of all recharge grids (mm)

Water balance is the water balance calculated at the considered date and using the run on value calculated at the previous day.

6.2.5 Pond output file “pond##.out”

The model produces a file “pond##.out” that lists the locations of the ponds and their corresponding aspect directions aspect directions. The ## in the file name replace the grid number where the listed ponds are located. This file can be used to plot the ponds on a map. It can be also used to correct the aspect direction at a node where representing a pond so that this pond can be eliminated from the model.

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