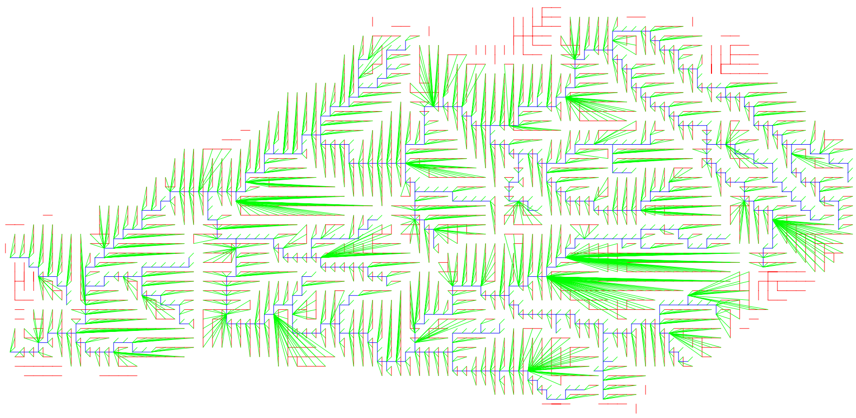
Recharge modelling for the West Bank aquifers

Groundwater Systems and Water Quality Programme

Commissioned Report CR/05/087N



BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT CR/05/087N

Recharge modelling for the West Bank aquifers

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Recharge; Model; Object-oriented.

Front cover

Cover figure shows runoff routing for Natuf catchment model

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Contents

APPENDICES

1 – Hydrograph analysis

2 – Description of SCS D-hydrographs

3 – Relationship of model grid with GIS grid

4 – Model output for the West Bank recharge model

FIGURES

TABLES

Foreword

The report has been prepared by British Geological Survey (BGS) for the Department for International Development (DFID) funded project "Sustainable Management of the West Bank and Gaza Aquifers" (SUSMAQ).

The primary aim of the SUSMAQ project is to support the Palestinian Water Authority (PWA) by improving the current understanding of the flow system of the aquifers of the West Bank and Gaza, and to assess the sustainability of the aquifers under a variety of economic, demographic and land use scenarios in terms of meeting the consequent water demand from aquifers. This is achieved through a set of management tools based on mathematical simulation of flow in the aquifers, a component of which is the recharge modelling.

Acknowledgements

As for all work, there are a number of people to acknowledge for the work undertaken in this report including PWA staff and the SUSMAQ team in Ramallah, who have provided data and contributed ideas to the development of the model and Clemens Messerschmid for his tireless field work and production of reports.

BGS staff members are also acknowledged for their contributions; Nick Robins and Denis Peach for their hydrogeological experience, Chris Jackson for his patient answering of object-oriented queries, Andrew Mckenzie, Brighid O Dochairtaigh and Helen Rutter for their prior knowledge of the West Bank and Roger Calow and Alan MacDonald for a glimpse into the softer side.

Executive Summary

Recharge can take two main forms, direct recharge from rainfall infiltrating the ground or indirect recharge from leakage from wadi beds. The recharge processes operating in the West Bank can be summarised as rainfall recharge, wadi recharge, urban recharge processes and irrigation losses. Rainfall recharge is the predominant form of recharge, whilst wadi recharge, urban and irrigation losses are only minor components. However, these minor components can be locally important.

The recharge processes operating in the Wadi Natuf catchment are varied and complex. The four main geological strata through which recharge takes place are:

- Jerusalam
- Upper Lower Beit Kahil
- Lower Beit Kahil
- Hebron

The main aquifer units are karstic which receive recharge once a wetting threshold is exceeded. This assumption is supported by field observations (Messerschmid, 2003) and a field experiment close to the study area (Lange et al., 2003). Other minor aquifers receive recharge and distribute water laterally to springs. Flow from springs, if not used for water supply or irrigation, can then be routed to other aquifer units or as loss from wadis.

High intensity rainfall can produce overland runoff and wadi flow. Flowing wadis loose water to all but the Yatta formation.

Recharge can, therefore, occur by two methods, direct infiltration from rainfall and from losses from wadi beds.

There are four main recharge processes operating in the aquifers of the West Bank;

1. Direct recharge from rainfall
2. Indirect recharge from wadi losses
3. Recharge from urban water supply and waste water proceses
4. Recharge from irrigation losses

The difference between rainfall and potential evaporation, known as effective rainfall, is the main control on direct recharge from rainfall. Rainfall is greatest in the north and west whereas potential evaporation is the highest in the south and east. The greatest potential for rainfall recharge is, therefore, in the north and west. Soil cover also controls the amount of rainfall recharge and is highly variable over the West Bank. In particular, the main soil types have patchy coverage, over only 30-50 % of the ground surface, the rest being bare rock. The patchiness of the soil means that soil moisture is not developed in the same way as for soils with uniform coverage.

To determine the rainfall recharge mechanisms operating in the West Bank, a combination of factors such as rainfall, potential evaporation, soil cover, land use, etc need to be assessed. Combining these factors mean that recharge processes based on soil moisture are most likely to be operating in the north-west of the West Bank. Elsewhere, direct recharge will be based on how the soil and rocks combined as single system respond to the balance between rainfall and evaporation (e.g. Lange et al., 2003).

Indirect recharge occurs due to wadi flows over the whole of the West Bank. Runoff from intense rainfall events will collect in valley bottoms and create surface water flows. Recharge from wadi beds will form the predominant source of recharge in the south and east of the West Bank, where the climate is more arid.

Urban recharge processes reflect leakage from pipes and sewers and increased runoff from paved surfaces, roofs, roads, etc. The enhanced runoff in the urban environment is routed to wadis and enhances flows after rainstorms. This can increase indirect recharge from wadi beds.

Losses from irrigation systems can enhance recharge. The main areas for irrigation are the north-west of the West Bank, in the vicinity of Jericho and the Upper Jordan Valley.

A significant amount of work has been undertaken on calculating recharge to the aquifers in the West Bank and in the Western Aquifer Basin by measuring discharge and abstraction as a surrogate for recharge. However, most of the estimates rely on empirical relationships between annual rainfall and recharge. Estimates undertaken using an empirical method are not physically based, but nonetheless can be used as a guide to determine whether the recharge calculated by the modelling are realistic. The estimates for the Western Aquifer Basin are around 350 $Mm^3\ a^{-1}$ and 800 $Mm^3\ a^{-1}$ for the West Bank as a whole.

To enable recharge to be calculated using a physical basis over aquifer outcrops, a distributed recharge model has been developed and tested. An existing object-oriented groundwater flow model has been adapted from an existing code. An object-oriented approach was chosen to enable a range of recharge mechanisms to be incorporated easily into the model. Recharge is calculated at a node, which is held on a grid and enables a distributed recharge estimate to be undertaken. Four types of recharge node can be specified; soil moisture balance method, wetting threshold, urban recharge process and irrigation losses. In addition to these mechanisms, runoff routing to wadis and subsequent infiltration is implemented.

1 Introduction

This report describes the application of a distributed recharge model to the aquifers of the West Bank. An analysis of recharge, i.e. the quantity of water that infiltrates from the land surface to the aquifer, is an essential input for simulation of flow in the aquifers. Recharge is a complex process, but quantification is critical in order to understand the total water availability from the West Bank aquifers. To aid the quantification of recharge, a distributed recharge model has been developed using object-oriented techniques. This recharge model has been adapted from an existing code to include the recharge mechanisms observed in the West Bank. The model has been applied to two areas, the Wadi Natuf catchment, as a pilot application, and the main outcrops of the aquifers underlying the West Bank.

This report builds on previous work (McKenzie et al., 2001), which summarises the recharge processes operating in the West Bank aquifer and the previous estimates of recharge and presents data collected during a visit to the project office in Ramallah. The work on the Wadi Natuf catchment is helped by various field visit reports undertaken by the SUSMAQ team (e.g. Messerschmid, 2003).

2 Recharge processes in the West Bank

2.1 INTRODUCTION

There are two main types of recharge; direct and indirect. Direct recharge is the amount of rainfall that percolates through the land surface to arrive at the water table and is defined as:

"…water added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone" (Lerner et al, 1990).

Indirect recharge is the water that reaches the water table by other, more circuitous routes. Examples of indirect routes include runoff to surface water courses and subsequent infiltration and localised recharge due to runoff ponding in shallow depressions and infiltrating into the ground.

In arid areas, which receive limited and usually unpredictable amounts of rainfall, indirect recharge predominates over direct recharge. Typically, in arid areas, intense rainfall events will result in runoff to wadis and losses from wadi beds will then form recharge. In semi-arid areas, direct recharge from the soil zone will be the predominant form of recharge.

Some of the recharge may be shallow, diverted from the main water table by perching and soil interflow to re-emerge at surface locally as springs and seepages.

2.2 SUMMARY OF RECHARGE PROCESSES

The main recharge processes operating in the West Bank (Figure 1) are:

1. Rainfall recharge
2. Runoff to wadis and subsequent infiltration
3. Urban recharge processes
4. Irrigation losses

The main component of recharge is likely to be rainfall recharge, however, the other components may be locally significant. For example, urban recharge processes will dominate in towns and cities overlying aquifer outcrops, or wadi infiltration in the more arid parts of the West Bank.

2.2.1 Rainfall recharge

The amount of rainfall recharge resulting from rainfall depends on:

- Rainfall; amount, intensity and temporal distribution
- Evapotranspiration
- Runoff
- Soil thickness and type
- Vegetation
- Slope
- Unsaturated zone properties

In humid climates the amount of soil-based or direct recharge is dependent on soil processes and how much evapotranspiration occurs from plants growing in the soil. The soil store can fill up as rainfall exceeds actual evaporation. Once the soil store is full, then water flows out of the base of the soil zone and becomes recharge.

In semi-arid and arid areas, however, the situation is more complex. The long-term average rainfall is lower, but also the rainfall is concentrated in more intense events. In arid areas, there is also no well-defined wet and dry season and rainfall is distributed over the whole year. In addition, evapotranspiration is much higher and soils less well developed. The combination of these factors mean that in arid zones soil moisture deficits are very high and direct recharge rarely occurs (Lloyd, 1980). In semi-arid zones, however, when rainfall occurs in sufficient quantity for soil moisture deficits to be reduced sufficiently infiltration may take place. The occurrence of topographic hollows and temporary ponding may assist the process locally.

2.2.2 Recharge from wadi losses

Rainfall in the West Bank is sporadic, especially in the arid areas to the south and east. Rainfall events can be of high intensity and typically storms with a rainfall intensity of between 10 to 15 mm/h can occur. These intense rainfall events lead to runoff to wadis where surface water flow will develop rapidly (Wheater and Al-Weshah, 2002). The wadis may recharge the groundwater system, either directly to the aquifer or via superficial deposits.

Recharge from wadi beds is an important recharge process as it can allow water that is initially lost to runoff during intense rainfall events to recharge the groundwater system. Wadi recharge is likely to be a small part of the overall water balance, but it is locally important. This is especially so in the more arid parts of the West Bank, in the south and east and where relatively impermeable deposits, such as the Abu Dis, exist.

2.2.3 Urban recharge processes

Characterising urban recharge processes is important where large towns or cities overly aquifer outcrops. When water and waste water is moved around the urban environment, a small, but significant proportion of it will be lost. Leakage from pressurized water mains and from breaks in sewers can, therefore, become a potential recharge source.

Additionally, the construction of impermeable surfaces such as roads, paved areas, etc in the urban environment enhances runoff. The roofs of buildings also contribute to stormwater runoff during rainfall events. The runoff resulting from these structures is collected and routed via storm drains to wadis. Foul sewers also empty into wadis, either directly or via sewage treatment works and these sources collectively offer a source of recharge.

Open spaces allow direct, soil-based recharge to occur. Recharge from this part of the urban environment, therefore, has also to be quantified.

2.2.4 Irrigation losses

Whilst crop water requirements can be calculated and water added based on this value, water is not generally applied efficiently and may provide potential for recharge. Transmission losses, associated with the transport of water to fields is another potential source.

There are many different methods of irrigation, but they can be placed into two categories; traditional methods and modern methods. The traditional methods include furrows, basins and flooding whilst the modern methods are sprinkler and drip systems (ARIJ, 1998). The modern methods are more efficient, i.e. losses are lower, than traditional methods.

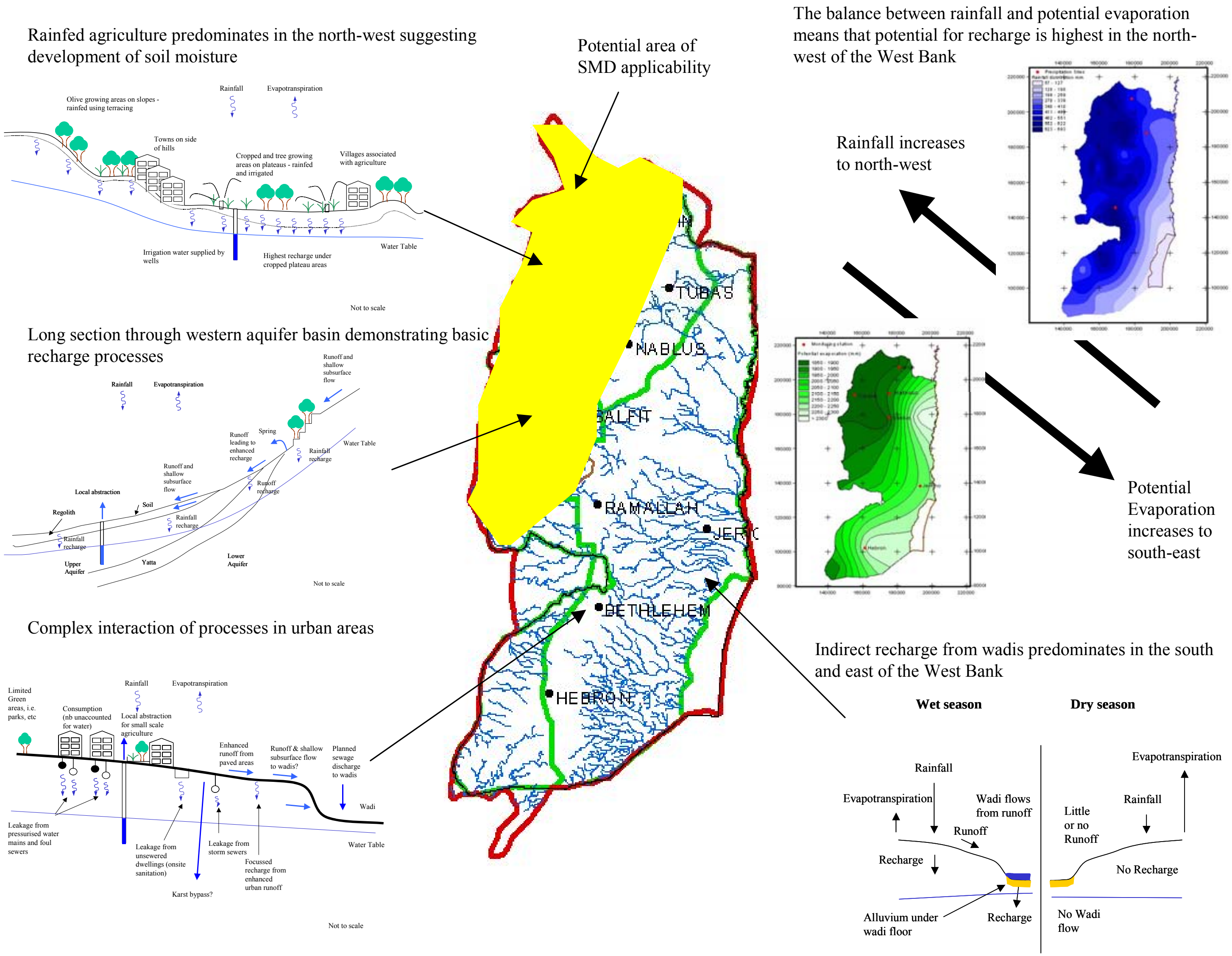


Figure 1 Summary of recharge processes operating in the West Bank

2.3 CONCEPTUAL MODEL OF RECHARGE PROCESSES IN THE WADI NATUF

2.3.1 Background

The Wadi Natuf has been a centre for detailed study during the SUSMAQ project. One of the components of this study is the calculation of recharge. To undertake this calculation, knowledge of the recharge processes operating in the Wadi Natuf catchment are required. These processes have been identified with the aid of SUSMAQ staff.

The calculation of recharge to the Wadi Natuf catchment has been informed by the results of a field experiment conducted by Lange et al. (2003). A sprinkler test was undertaken on an outcrop close to the area of the Wadi Natuf. The amount applied to the plot was known and the runoff measured, leaving the difference as recharge. Although only one test has been carried out at the site, this represents a valuable source of data. The field site has been subsequently surveyed and reported in Messerschmid (2002).

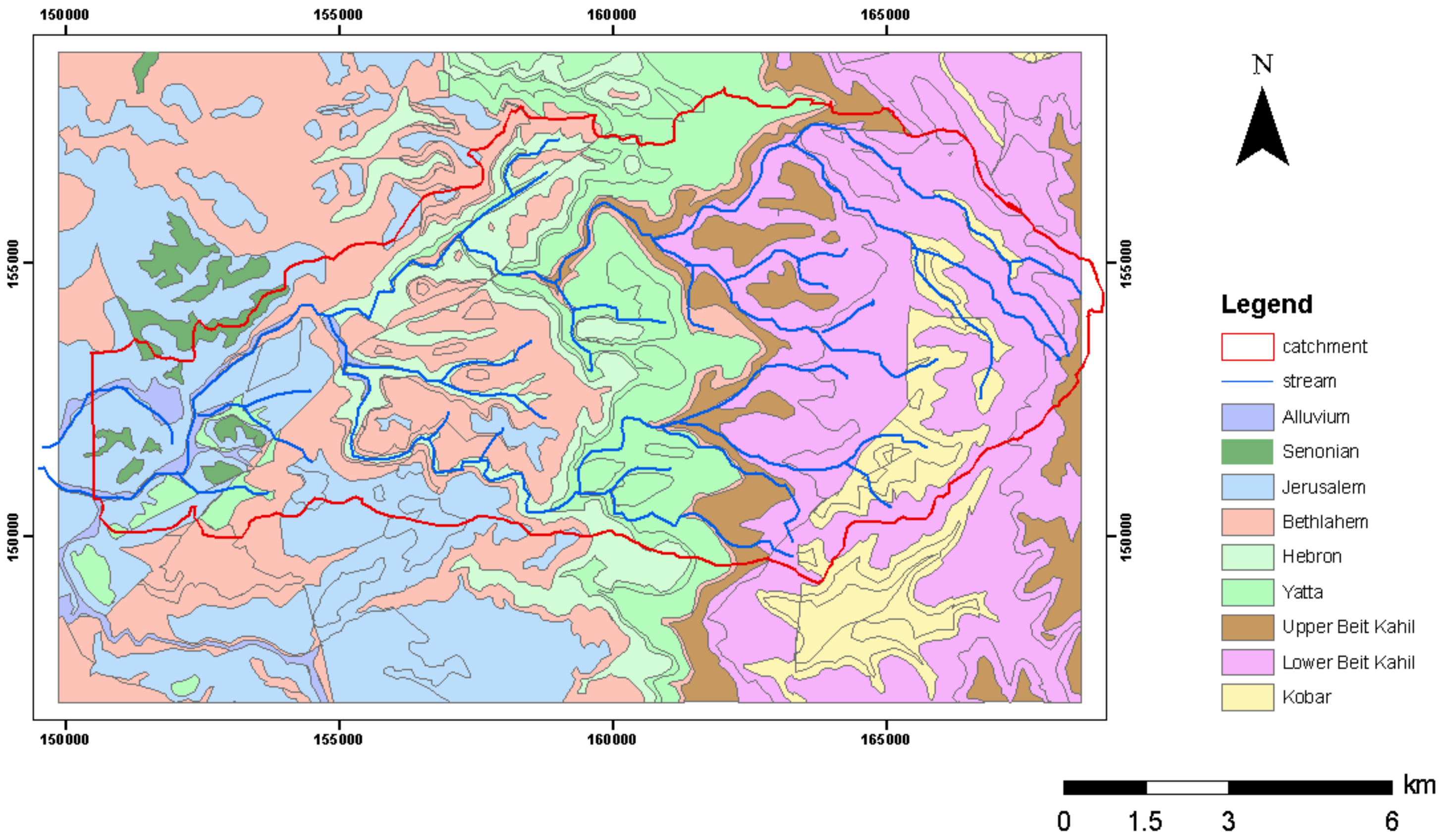


Figure 2 Geological map of the Natuf catchment

2.3.2 Hydrogeology

The groundwater system is normally conceptualised as two main aquifer units; Upper and Lower Aquifer separated by the Yatta, which is generally considered to be an aquitard. The reality is more complex and the Upper and Lower aquifer are themselves made up of different strata (Figure 2). Table 1 summarises the main hydrogeological units in the Upper and Lower aquifers. The geological strata in the West Bank have been assessed for their potential to produce recharge to the unsaturated zone ("Potential for recharge") and their potential for the geological unit to transmit water ("Potential for aquifer").

Table 1 Potential for recharge in West Bank

Formation			**Potential for recharge**	**Perched springs**	**Potential for aquifer**	**Ranking**	**Notes**
Israeli	Palestinian						
Bi'na	Jerusalem		+++	NO	+++	1	Eastern Aquifer Basin forms two aquifer systems
Weradim		UPPER AQUIFER	+	YES (forced out by Kefar Sha'ul)	+	2	Dry in Eastern Aquifer as WT too low
Kefar Sha'ul	Bethlehem		+-	NO (possible)	+-/-	3	Poor aquifer/aquitard
Amminadav	Hebron		++	NO	+++	1	
Moza			--	NO	--	4	Not always present
Bet Meir	Yatta		+-	YES	-/+	3	Normally aquitard, but can be a good aquifer
Kesalon	Upper Beit Kahil		+	YES (few)	+-	2	Not always top Lower but locally intermediate aquifer.
Soreq			+/+-	YES	+-	2	Horizontal layers of Marls inhibit vertical movement and produced perched system
Giv'at Ye'arim	Lower Beit Kahil	LOWER AQUIFER	++/+++	NO	++	1	Dependant on fractures
Kefira			+++	NO	+++	1	Fractured, but always produces good flow from wells
Qatana			-	NO	-	4	Aquitard
Ein Qinya			++	YES	++	4	Good local aquifer, but does not feed main aquifers

SPRINGS

There are over 130 springs identified in the Natuf catchment, with a total estimated flow of 0.5 $Mm^3\ a^{-1}$ (~1400 $m^3\ d^{-1}$). The vast majority of the springs issue around Beitillu where there are some 101 springs. Springs are small scale, localized parts of the system and the most important formations containing these include:

- Soreq – alternating layers of marl create springs at their outcrop
- Kesalon – some portions are marly which forms spring lines
- Bet Meir – springs from over blue clay at base

The springs issue almost entirely (>90%) from the lower Kesalon, where it rests on the first marls of Upper Soreq. However, the outcrop of the Kesalon is not sufficient to get enough recharge for this springflow. It is evident, that Kesalon and Beit Meir act as a connected perched aquifer.

Springs generally issue on the western exposed slopes of the hills (Figure 3). Where the Kesalon outcrops on eastern exposed slopes, springs are only found in exceptional cases. This is due to the general dip of formation, which is towards the west.

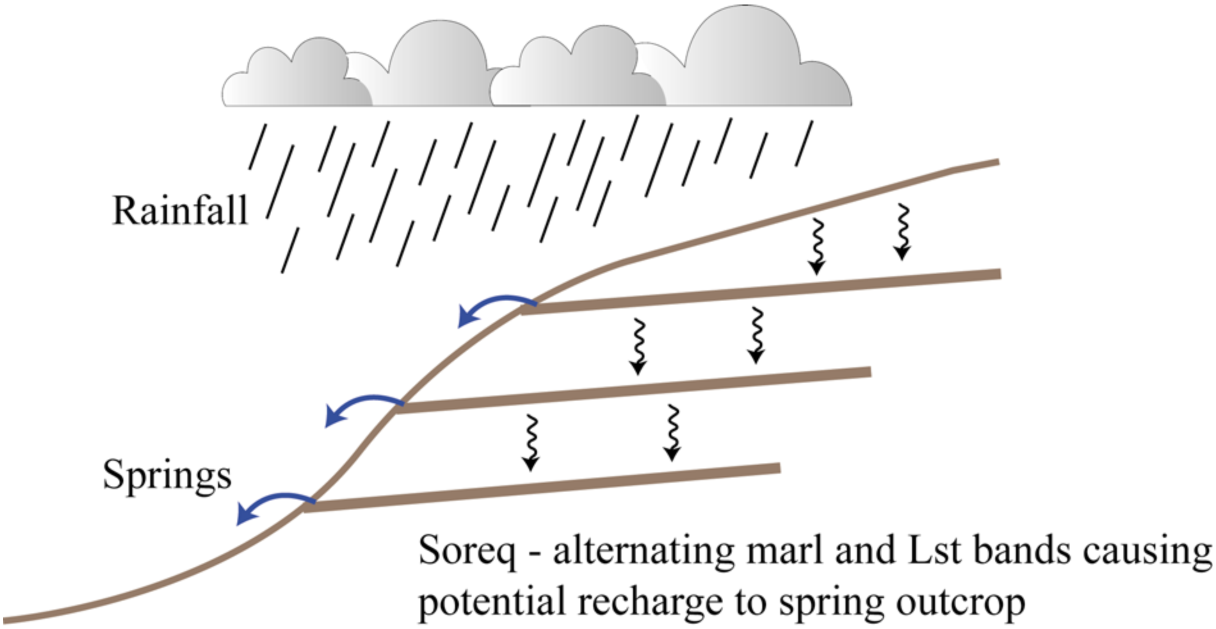


Figure 3 Springs issuing from Soreq due to alternate layering of marl bands

WADIS AND THEIR INTERACTION WITH THE GROUNDWATER SYSTEM

The Wadi Natuf surface water system consists of a number of tributaries (see Figure 2). The Wadis crossing the catchment are fed by runoff and springflow. Runoff is only generated during high intensity rainfall events. Examples of runoff based wadi flow can be found in field reports (Messerchmid, 2003). Spring fed portions of the Wadis in the study area have been observed in Wadi Zarqa, again during field visits. Water flowing in the Wadis can then be transmitted downstream or lost to the groundwater system.

Wadi losses are largely controlled by the geology underlying the wadi bed. From various field visits, it can be concluded, that the principal formations that allow or facilitate wadi losses are Hebron, Upper Bethlehem (Weradim) and Jerusalem formations for the upper aquifer, and for the Lower Aquifer Kesalon. The Upper Yatta (e.g. Wadi Dilb) and Soreq (e.g. Wadi Zarqa) do not promote wadi losses from occurring and flow tends to accrete.

Due to the limitation on access to the catchment, no direct observation been made for the Lower Bethlehem (Kefar Sha'ul) lower Yatta (Beit Meir) and with Lower Beit Kahil formations (Kefira and Giv'at Ye'arim). However, both the Lower Beit Kahil formations allow a considerable amount of wadi losses, due to their karstification and aquifer potential.

2.3.3 Discussion of recharge processes

The main outcrop areas are karstic and do not have significant soil cover. The idealisation of recharge processes occurring in the Wadi Natuf is illustrated in Figure 4. Rainfall occurs over a combination of bare rock and soils. Once the system is sufficiently wetted up, then both runoff and infiltration will occur.

The understanding of the recharge processes occurring in the Wadi Natuf catchment are incomplete and the following issues remain:

- Extent of fracturing associated with bare rock – can this be determined and what implications are there for water that by-passes the soil zone and goes directly to the unsaturated zone, i.e. by-pass recharge?
- What is nature of soil pockets, how deep are they?
- How does the weathering crust (Nari) affect the wetting up of the system?
- What is the nature and distribution of epi-karst in the system?
- What happens to runoff? Lange et al (2003) predicts runoff as a high percentage of rainfall. What proportion of it reaches wadis? Does ponding occur leading to evaporation?

Soil-based rainfall recharge could also be occurring where extensive soils exists as in the western part of Wadi Natuf. A soil moisture balance approach can therefore be used to estimate recharge in these areas.

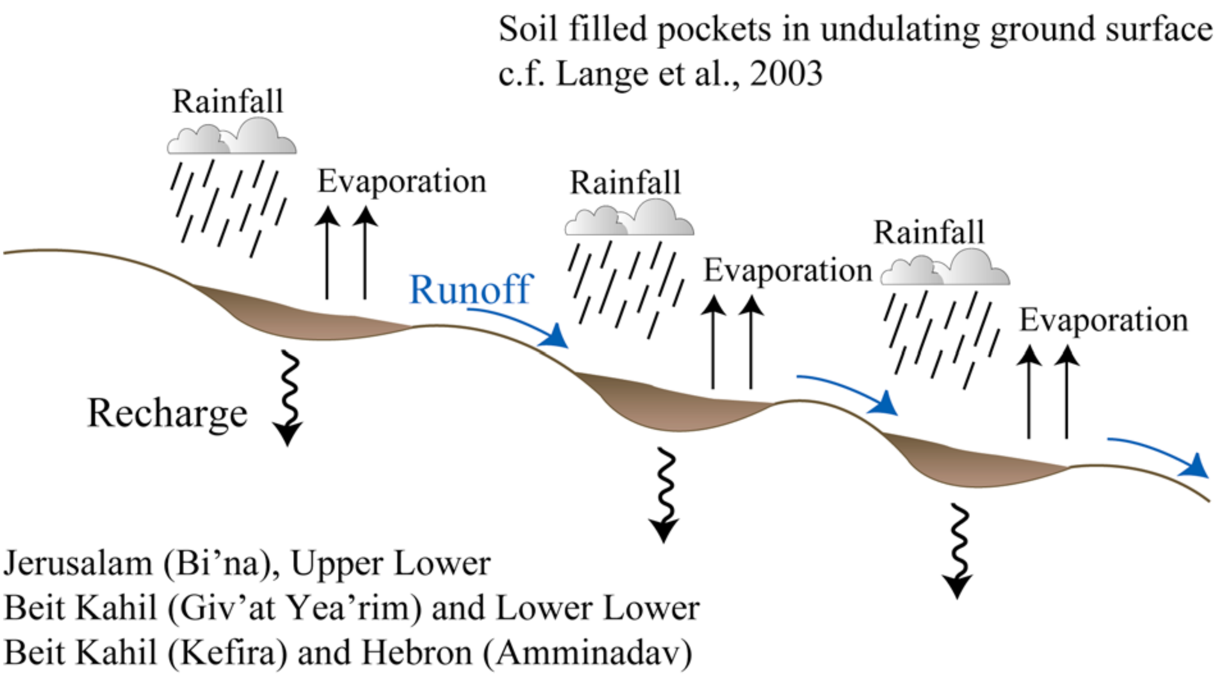


Figure 4 Recharge processes on karstic terrain.

2.4 CONCEPTUAL MODEL OF RECHARGE PROCESSES IN THE WEST BANK

2.4.1 Introduction

The recharge processes occurring to the groundwater systems underlying the West Bank are complex. The karstic nature of the aquifers, climatic variation from semi-arid to arid areas over the West Bank, local springs, flow to wadis, and urban and irrigation processes mean recharge processes are difficult to quantify on a regional scale. However, recharge needs to be quantified regionally scale for water balance purposes and for use as an input to regional groundwater models. That being so, catchment scale studies, such as the Wadi Natuf investigation, are more appropriate for determining recharge processes operating in the groundwater systems underlying the West Bank.

2.4.2 Factors influencing rainfall recharge

Rainfall recharge processes operating in the West Bank are controlled by a number of factors. These factors vary spatially and it is the interaction between these factors, which determine how recharge varies over the West Bank. The factors can be summarised as follows:

- Rainfall and evapotransiration
- Climatic zones
- Geology
- Soil type and thickness of soils
- Topography and slopes
- Landuse and the influence of human activity
- Wadis
- The characteristics of the unsaturated zone

These factors are described in more detail below.

Other, locally important recharge processes are urban processes and the influence of agriculture on recharge. Agricultural practice can modify recharge by the addition of water from irrigation losses and may have an impact on runoff by changes to the landscape for farming, i.e. olive plantations.

RAINFALL AND EVAPORATION

Both rainfall and potential evaporation vary significantly over the West Bank. Rainfall is partly orographic and reaches a maximum in the north and west of the study area. The maximum long-term average (LTA) rainfall is 650 mm a^{-1} and occurs on the highest ground. The lowest rainfall occurs in the south and east of the West Bank, where the LTA rainfall is just under 100 mm a^{-1}.

Potential evaporation also varies over the West Bank reaching a maximum in the south-east towards the Dead Sea. The range of potential evaporation is 1850 mm a^{-1} in the north to 2300 mm a^{-1} in the south-east.

Since recharge is driven by the balance between rainfall and potential evaporation, the highest potential for recharge is in the north-west of the West Bank (see McKenzie et al., 2001; ARIJ, 1998).

CLIMATIC ZONES

It is important to determine the aridity of the climate and how this is distributed to enable the types of recharge processes that are operating to be determined. In humid and semi-arid climates, direct, soil-based recharge predominates. In arid climates, where rainfall is lower and consists of high intensity events, indirect recharge such as wadi recharge is also important.

The West Bank can be split into four climatic zones based on rainfall distribution:

1. Rainfall < 100 mm a^{-1} – South-east of the West Bank

2. 100 mm a^{-1} < Rainfall < 400 mm a^{-1} – Eastern basin and the southern part of the western basin
3. 400 mm a^{-1} < Rainfall < 600 mm a^{-1} - Central and northern part of the Western aquifer basin and the north-eastern aquifer basin
4. 600 mm a^{-1} < Rainfall < 1200 mm a^{-1} – Top of mountains

The majority of the West Bank can, therefore, be defined as receiving less than 600 mm a^{-1}. Direct recharge will occur when soil moisture deficits are exceeded for the semi-arid areas, where a good soil cover exists (Lloyd, 1980). In arid areas, where high evapotranspiration, sporadic rainfall and poorly developed soil exist, soil moisture deficits are very high and direct recharge is rare and indirect recharge will predominate (Lloyd, 1980; de Vries and Simmers, 2002). Typically, recharge will occur from runoff to wadis resulting from storm events and subsequent infiltration from these wadi beds (Wheater and Al-Weshah, 2002).

GEOLOGY

Geology controls recharge both directly through the nature of the rocks at outcrop and indirectly through topography, slope and the nature of soils. The soil zone is where the balance between rainfall and evapotranspiration is determined.

Runoff is determined by the steepness of slopes and the nature of the underlying rocks. Generally, the greatest runoff will occur over the less permeable deposits, examples of these include the Yatta and the Abu Dis. The Abu Dis is especially important in the Eastern Basin where the low infiltration capacity combined with limited soil coverage (see below) and arid climatic conditions result in high runoff to wadis and indirect recharge.

The hydrogeology of particular outcrops can be summarised as four main types:

1. Highly transmissive readily allowing recharge to the water table (e.g. Lower Beit Kahil, Hebron and Jeusalem)
2. Moderately transmissive allowing limited recharge (e.g. Upper Beit Kahil)
3. Relatively impermeable resulting in high runoff, e.g. Yatta and Abu Dis
4. Perched systems which produce localised springs systems, e.g. Kobar or Soreq.

SOIL TYPE AND THICKNESS

Large scale soil maps are available for the West Bank (e.g. Fig 10. ARIJ, 1998) and a summary of the main soil types found in the West Bank is presented in Table 2. The predominant soil types are Terra Rosa, Brown Rendzina and Pale Rendzina (41% west Bank) and Brown Rendzina and Pale Rendzina (26% of the West Bank). Both these soil types are found in the central and western part of the West Bank. These soil types support a variety of agriculture including field crops (mainly wheat and barley), grapes and olives (ARIJ, 1998). Typically these soils are found in rocky areas where 30 – 50 % of the area is bare rock. This distribution of soils creates a problem for soil defining thickness. The soils are described as being "contained in pockets and cracks which may be deep" (ARIJ, 1998). The combination of soils with bare rock has implications for the recharge processes. Development of soil moisture may be inhibited and runoff increased in comparison with areas where soil is more evenly distributed over the surface.

The other main groups of soils are found in the eastern slopes of the Jordan valley. Four main soil types occur;

1. Brown lithosols and Loesoils Arid Brown soils

2. Brown lithosoils and Leosoils Serozems
3. Regosols
4. Bare Rocks and Desert lithosols

All these soil types suggest increasing aridity to the south and east of the West Bank with limited crop development and increased runoff.

Table 2 Summary of the main soil types in the West Bank

Soil Type	Total area (ha)	Description of soil thickness	Proportion of rock outcrop (%)	Crops grown
Terra Rosa, Brown Rendzina and Pale Rendzina	235210	Soils in pockets and cracks may be deep	30 – 50	Field crops (wheat barley), vineyards, olives and fruit tress in valley sides
Brown Rendzinaz and Pale Rendzinas	145698		30 – 50	Field crops (wheat barley), vineyards, olives and fruit tress in valley sides
Brown Lithosols and Loessial Arid Brown Soils	48391		50 - 60	Field crops or grazing
Brown Lithosols and Loessial Serozams	24485	Rock outcrops “many”		Winter crops
Bare rocks and desert lithosols	19573	Very shallow		Grazing

TOPOGRAPHY AND SLOPES

The topography of the West Bank is dominated by the major anti-clinal structure that runs approximate south-north. The land surface rises from the Mediterranean Sea, reaching a height of 900 m asl before falling to an elevation of – 250 m sl in the Jordan Valley. Cutting through the mountains are numerous steep sided wadis. Slope maps (e.g. Fig 2.2 in ARIJ, 1998) illustrate the distribution of hillslope. Human activity such as farming, especially olive plantations, have modified the slopes by terracing, so increasing the potential for recharge. The implication for recharge is that steep-sided slopes result in enhanced runoff. When runoff does occur, as a result of intense rainfall events, then water drains to the valley floor and creates flow in the wadi. The fraction of rainfall as runoff is, therefore, high, but runoff only occurs during high intensive rainfall events.

LANDUSE AND THE INFLUENCE OF HUMAN ACTIVITY

Table 3 presents the main landuse types, the predominant Palestinian landuse is agriculture (cultivated areas), with an area of 1682 km^2 and covering 28.9 % of the West Bank. Of this land area, only 6% is irrigated, the rest is rain fed (ARIJ, 1998). The preponderance of rain fed agriculture suggests extensive soils in which soil moisture can develop. The majority of agriculture, outside the Jordan valley, is undertaken in the Northern Governerates (see p82; ARIJ, 1998).

The type of agriculture and areas involved within the Israeli settlements are unknown.

Other types of land with implications for rainfall recharge are the forests and rough grazing.

Table 3 Landuse distribution in the West Bank (after ARIJ, 1998)

Type	**Area (dunums)**	**Area (km^2)**	**Percentage of West Bank**
Palestinian built-up areas	213 453.0	0.7	3.67
Israeli built-up areas	77 788.0	0.9	1.34
Closed Military areas	1 177 540.0	0.7	20.23
Military bases	16 523.7	0.5	0.28
State land	1 410 884.6	1.3	24.23
Nature reserves	315 153.3	0.5	5.42
Forests	32 834.3	0.9	0.56
Dead Sea	177 410.0	0.6	3.05
Cultivated areas	1 682 000.0	0.7	28.90
Other	718 413.1	1.1	12.32
TOTAL	7820.0	7.9	100.00

Note: Other landuse type represents dumping sites, industrial zones, unused land or land used for grazing.

WADIS

A large number of wadis exist in the West Bank, either flowing westwards towards the Mediterranean or eastward towards the River Jordan.

A steady source of water is required to enable the wadis to flow all year round. This could include springs, waste water discharges, etc but re-infiltration must be minimal. Examples of gauges in wadis in the West Bank that flow continuously include Wadi Soreq at Yesodot and Wadi Ayyalon at Bet Dagan-Yehud Road.

Wadis only flow intermittently where flow is not supported by springs or other discharge. This is due to the nature of rainfall and the associated flashy runoff; typically these type of wadis will flow for only a few days each year. The frequency of flow suggests that runoff is not commonplace and that rainfall events of a certain threshold intensity are required to initiate runoff (McKenzie et al., 2001). Examples of wadis with intermittent flows include the Natuf which only flows for between 10 and 25 days a year.

Wadis also have a role in providing indirect recharge to the groundwater system. Runoff, especially in the more arid parts of the system, for example the Abu Dis in the southern part of the Eastern Aquifer Basin, results in significant flows in the wadis. Losses through the wadi beds enable runoff collected in the wadis to recharge the groundwater system. Wadi flows can also accumulate over less permeable deposits, such as the Yatta, and then flow is lost once the wadi bed passes over more permeable deposits. Wadis, therefore, have an important role in collecting runoff and promoting indirect recharge.

THE UNSATURATED ZONE

Not all the infiltration becomes recharge because the unsaturated zone may not be capable of transporting it all and some may re-emerge as springs and seepages possibly aided by the topography. The unsaturated zone determines the amount of recharge that reaches the water table, where recharge arrives and how long it takes to get there. A knowledge, therefore, of the nature of the unsaturated zone is essential in determining these factors.

In the Western Aquifer Basin the depth to the water table is typically 100 to 300 m below the groundwater surface (see Fig 3-8; SUSMAQ, 2003b). An unsaturated zone that is hundred's of metres thick will significant delay the arrival of recharge at the water table. Work has been undertaken to understand the different types of hydrograph response in the West Bank aquifers and is presented in Appendix 1.

The other feature of the unsaturated zone is its karstic nature and layering. Water can move both vertically and laterally in these conditions. Lateral movement, especially in the Soreq, produces localised springs, which can intercept infiltration on its way to the water table. The timescale over which water travels down through the unsaturated zone is also controlled by the karst system. A study in the Soreq cave (Kaufman et al., 2003) compared the rate of drips in the cave to rainfall events. The study showed that after intense rainfall events two kinds of response, one fast and one slow, were observed. This was put forward as evidence that water travelled at different timescales through the unsaturated zone.

2.5 JUSTIFICATION OF MODELLING APPROACHES

Recharge in semi-arid regions can be calculated using a soil moisture balance method (e.g. Lloyd, 1980; Rushton, 1988). However, a more cautious approach is advocated by Lerner el al. (1990), who states that the soil moisture balance method has been developed for humid climates and "has less validity in arid and semi-arid climates". However, provided certain conditions are met, soil moisture balance methods can be used (Lerner et al., 1990). These conditions are:

Whole Year: $p + i > 500$

Wet season: $et_p < 1.5(p + i)$

Dry Season: $et_p < 3(p + i)$

Where:

p – precipitation (mm a^{-1})

i – irrigation (mm a^{-1})

et_p – potential evaporation (mm a^{-1})

These conditions are met over a significant proportion of the Western Aquifer Basin outcrop to the north of Jerusalem (see Figs 7 and 8; McKenzie et al, 2001; Fig 5.3 SUSMAQ, 2003a).

To consider whether soil moisture balance methods should be used, other factors need to be taken into account. Lerner et al. (1990) state that soil moisture balance methods are valid where:

"…seasonal patterns of recharge, well developed soils which do not dry out completely, when potential and actual evaporation are of similar sizes, and with precipitation that is widespread and uniform".

These conditions are met in the northern part of the outcrop of the Western Aquifer Basin and in some areas of the North-Eastern Basin. Further evidence for appropriate conditions to apply a soil moisture balance approach is the predominance of rain fed agriculture in the northern part of the West Bank (ARIJ, 1998).

2.6 PREVIOUS ESTIMATES OF RECHARGE

There have been numerous estimates of recharge undertaken in the West Bank, e.g. McKenzie et al. (2001) and SUSMAQ (2003a). The details of these studies are not discussed here, but the main results are summarised to provide a context for the results produced by the recharge model described below.

A summary of the long-term average estimates of recharge for the geological basins within the West Bank are presented in Table 4. A consistent recharge estimate is reached for the Western Aquifer Basin of around 350 $Mm^3\ a^{-1}$, which is confirmed by SUSMAQ (2003a). Recharge estimates for the Eastern Aquifer Basin, again, reach a consistent value of 130 $Mm^3\ a^{-1}$, whilst few estimates are available for the North-Eastern Basin. Additionally, a small number of studies present estimates for the whole of the West Bank. These estimates achieve a consistent value of just over 800 $Mm^3\ a^{-1}$, which is more than 200 $Mm^3\ a^{-1}$ greater than the sum of the estimates for each individual basin.

Table 4 Previous recharge estimates (from McKenzie, 2001)

Basin	**Minimum $Mm^3\ a^{-1}$**	**Source**	**Maximum $Mm^3\ a^{-1}$**	**Source**
Western	317.5	Goldschmidt and Jacobs (1958)	366	EXACT
Eastern	118.5	Guttman and Zukerman (1995)	197	CDM (1998)
North-Eastern	145	EXACT	N/a	
West Bank	800	Guttman (1995)	836	HSI 1997

For the Eastern Basin, the minimum and maximum is provided by the time variant recharge estimates by Guttman (1998), in which a model was run from 1969 to 1994. The minimum estimate is 60 $Mm^3\ a^{-1}$ for a dry year and 460 $Mm^3\ a^{-1}$ for a wet year

3 Description of object-oriented recharge model

3.1 INTRODUCTION

The object oriented (OO) recharge model is currently being developed for the recharge calculation in regional studies, both in the UK and overseas. The model is a distributed recharge model that exploits OO techniques. Recharge is calculated at nodes held on grids. Nodes can be given different types of recharge calculation using inheritance. In principle any number of recharge node types can be specified. Currently there are four types of nodes; soil moisture deficit recharge calculation, an arid zone accounting method, a method that calculates recharge from urban areas and a method that calculates recharge from irrigated areas. In addition to the recharge calculation objects, there are data objects which hold distributed data. The data objects read data on grids that are independent of the calculation grid enabling the model size to be changed without the need to alter the data grids.

The calculation of recharge is undertaken within a series of recharge objects held within a grid. Due to the flexibility and power of OO coding these recharge objects can be updated as the understanding of recharge processes increases. Any number of recharge calculation objects can be specified for a grid and in turn any number of grids can be specified. It is, therefore, possible to have more detailed recharge calculations where it is necessary by specifying a grid with a finer mesh.

Each type of data is held in its own object and a standard request is sent from other parts of the model to obtain data from the correct object. This simplifies updating or changing the data object. This is an extremely powerful feature of OO coding and allows development of data objects, for example, a statistical rainfall object could be used instead of the current rainfall data object.

Understanding recharge processes in any groundwater system is an on-going process. The overall aim of the recharge model is to be flexible to cope with recharge processes that vary spatially over a study area and be able to change during a project as understanding increases. The OO recharge model offers this flexibility and can be exploited to enable both a defensible water resources assessment and provide an input to a regional groundwater model.

3.2 DESCRIPTION OF THE OBJECTS AND THEIR 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 (Figure 5). 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).

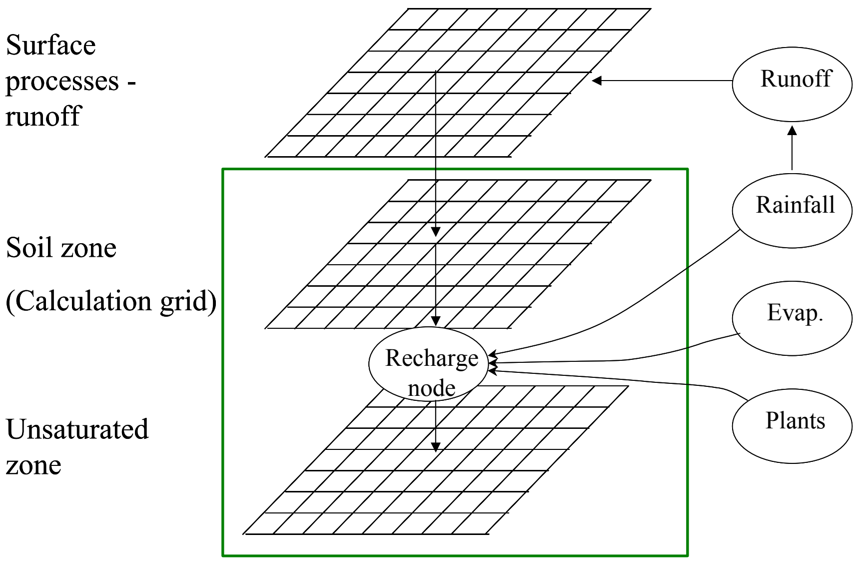


Figure 5 Relationship between grids in the recharge model

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 are then calculated 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. Data are exported from the GIS as ascii arrays (i.e. grid files) and either directly read by the model such as the topography, aspect map etc., or processed using a spreadsheet to be in the correct format for the model input file.

The type of recharge calculation at each node can be chosen using inheritance. Presently there are four recharge calculation methods in the model; the SMD method, a soil moisture balance approach that is suitable for semi-arid regions and two calculation methods that represent the recharge processes in urban areas and in irrigated areas. The relationship between the four node types is illustrated in Figure 6.

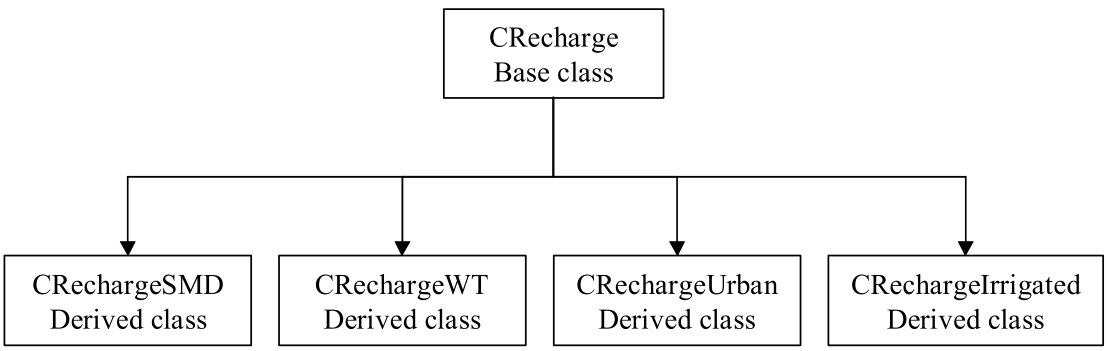


Figure 6 Relationship between recharge calculation nodes

Figure 6 shows that there are two grids associated with the calculation grid; surface processes grid and an unsaturated zone grid. Runoff is handled using the surface processes grid and this grid determines the routing of runoff based a Digital Terrain Model (DTM). The DTM is processed to provide directions of slope based on the cardinal points of the compass (i.e. north, south, east and west). The recharge model then links the associated nodes to create the routing pathways. The runoff calculated by each node is routed down to the lowest point in the system during the calculation time step,

The unsaturated zone object is used to determine the amount and timing of rainfall recharge leaving the soil zone and reaching the water table. Recharge, calculated in the node objects, is stored in equivalent nodes in the unsaturated zone object. Zones to represent outcrops of different geologies can be specified within the unsaturated zone grid. These zones can be used for recharge accounting and for routing lateral recharge. Presently, two mechanisms are included in the unsaturated zone object:

1. Lateral routing from one geological zone to the nearest neighbour in another geological zone.
2. Delaying the arrival of rainfall recharge to the water table.

3.2.1 Description of objects used within the model

The main objects currently in the model can be summarized as follows:

- Calculation objects
    - COOBRM – 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
    - CRecharge – object where recharge calculation takes place
    - CClock – handles time-step and updates date
    - CWadi – object that holds wadi node objects where wadi flow routing calculation takes place.
    - CSpring – Spring objects that hold spring flow information
- Data objects
    - CRain –Inputs and stores rainfall on a grid basis and distributes via LTA rainfall
    - CEvap –Inputs and stores PE on a grid basis
    - CPlants – Inputs and stores landuse data and C & D values for SMD calculation
    - CRunoff – Inputs and stores runoff data on a grid basis
    - CAspectMap – stores data for aspect directions at the recharge nodes
    - CTopoMap – stores data for topographical settings at the recharge nodes
- Other objects
    - CUnsatGrid – stores recharge calculated at each nodes
    - COutput – an object that manages the output files of the models.

The relationship between the objects (i.e. the framework) is illustrated in Figure 7. The main object is COOBRM which holds all the other objects. This object initiates the grid object which creates the grids of calculation nodes (CRecharge). Data are held within the data objects; CRain, CEvap, CPlants and CRunoff. When a recharge calculation is carried out at a node, then a request for data is sent to the relevant data object and the required data are returned to the recharge calculation node. The recharge calculated by the CRecharge object is stored in nodes within the CUnsatgrid object. Runoff is stored in nodes within the CWadi object to enable routing of runoff to take place. The control of the time-step and storage of the date are handled by the Clock object (CClock).

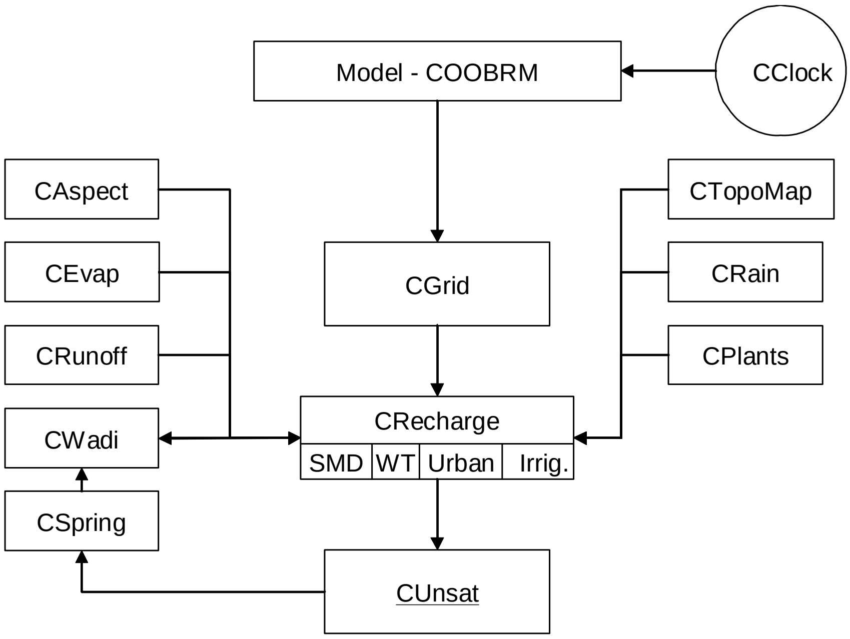


Figure 7 Framework of recharge model

The relationship between the calculation objects is illustrated in Figure 8. The calculations start at the recharge node level. The recharge nodes request data from the grid object, process them and calculate runoff and recharge. The runoff is passed from one node to another until it is delivered to the river object while the calculated recharge is passed directly to the unsaturated node objects. The recharge passed to the unsaturated node is then split into two parts. The first is passed to the spring objects which discharge it to the river. The second part is stored at the unsaturated nodes as recharge.

The total water at the river resulting from the surface routing and spring flows is routed downstream and considered as the surface water flow. It is assumed that the river object loses part of this water to the unsaturated node, which adds 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 values of this time step.

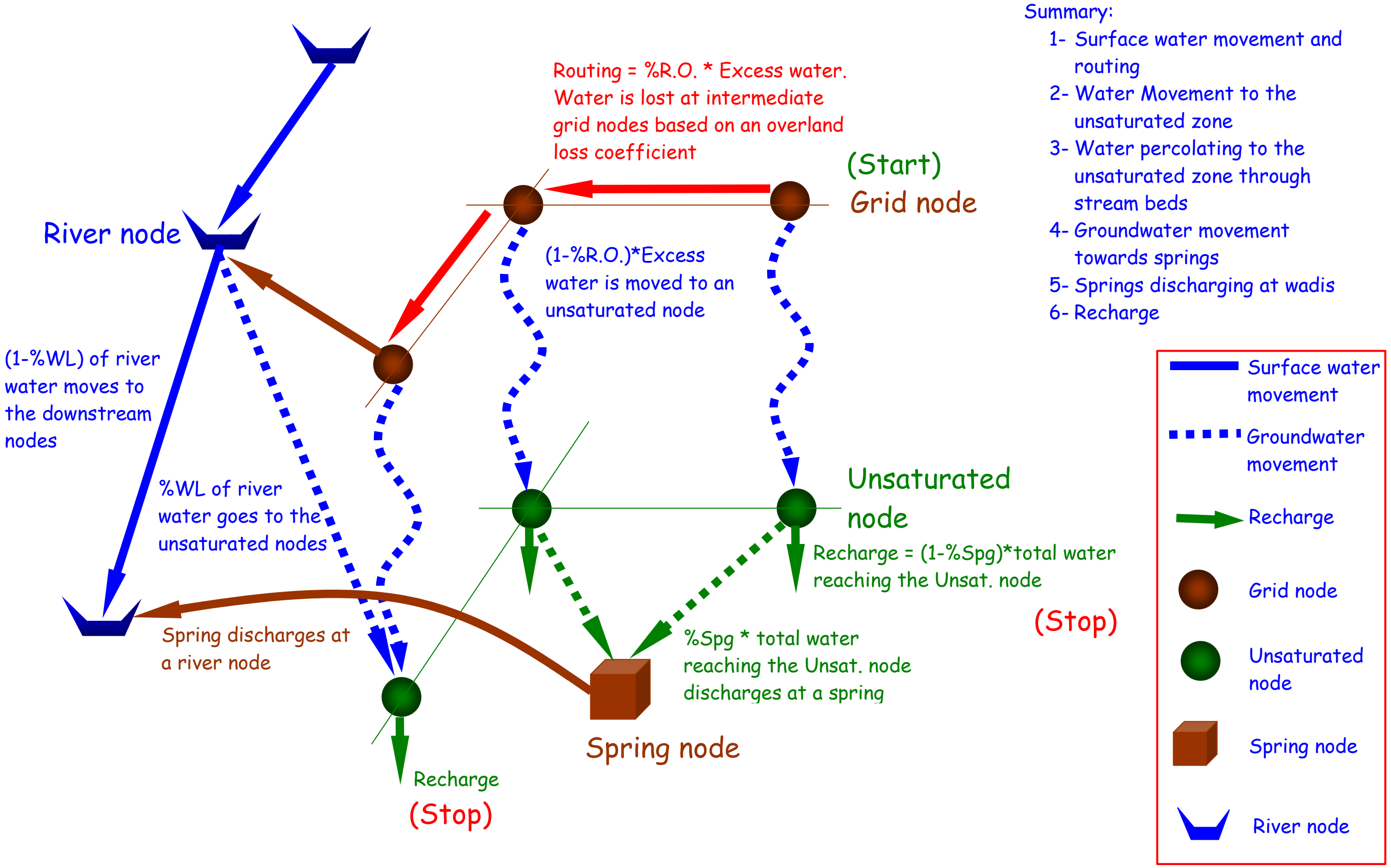


Figure 8 Outline of the calculation procedure

3.2.2 RECHARGE CALCULATION METHOD

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 the runoff, the potential evaporation and the soil moisture deficit are accounted for. 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 greater than the quantity of water minus the quantity of runoff, water will be lost from the soil by evapo-transpiration by plants. However, the quantity of water lost from the soil is dependent on the value of 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 9. 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 and 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 always to be equal to the value D.

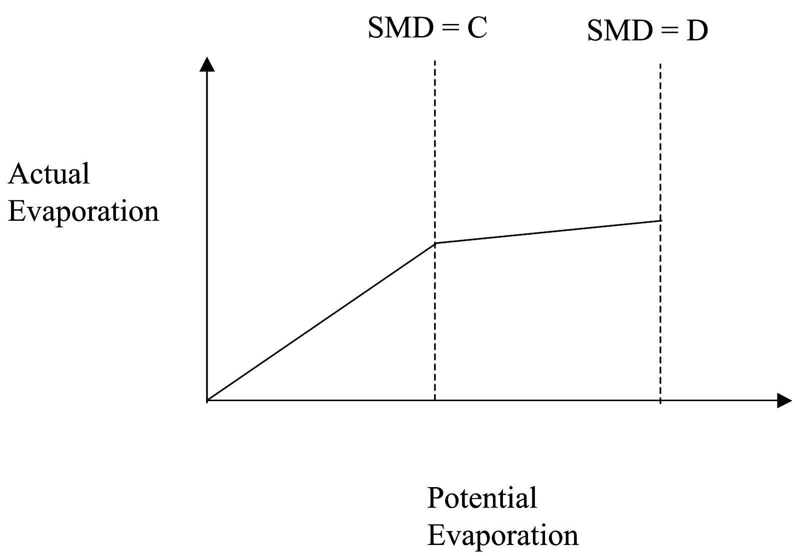


Figure 9 Relationship between actual evaporation and potential evaporation

When the SMD reaches a value of zero, the excess quantity of rainfall is considered as potential recharge.

The steps required to undertake an SMD method are outlined below and are presented as a flowchart in Figure 10. Further details can be found in Lerner et al. (1990).

1. Calculation of actual evaporation

If SMD $<$ C or R $>=$ PE: AE = PE

However, if C $<$ SMD $<$ D and R $<$ PE: AE = R + (EF x (PE – R))

Where EF is an empirical factor.

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)

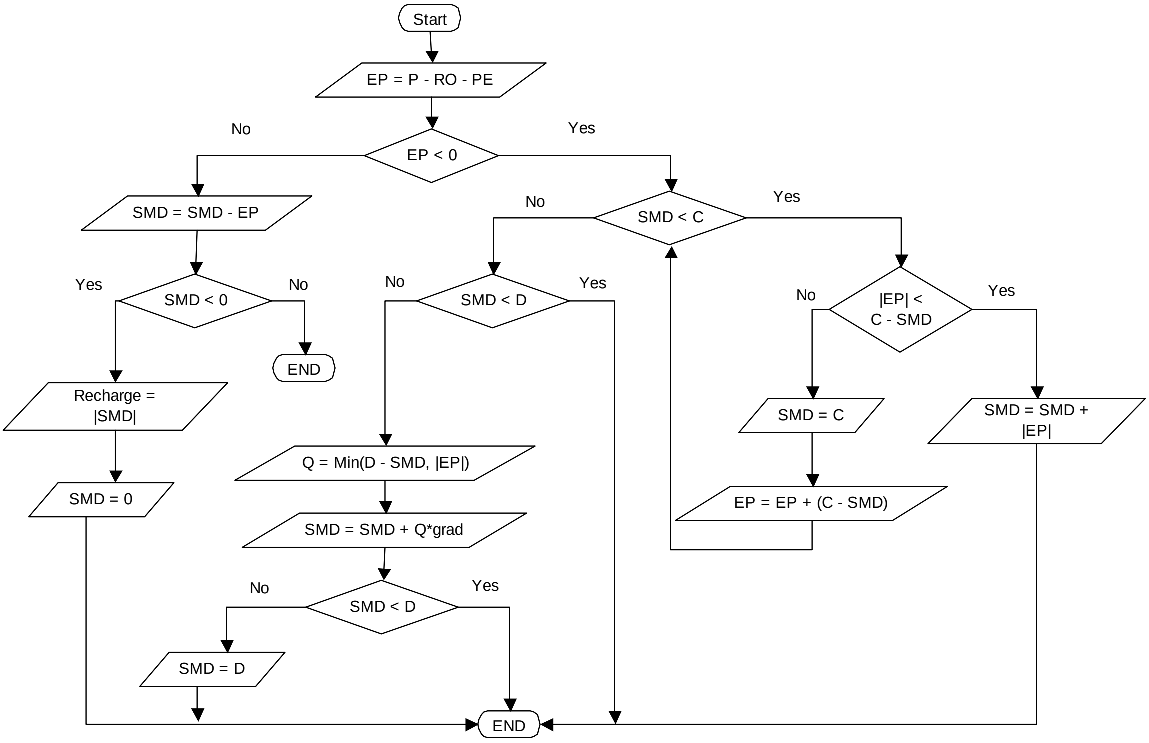


Figure 10 Flowchart for SMD method of recharge calculation

WETTING THRESHOLD METHOD

The most important reason that prevents applying the conventional method to estimate recharge for areas in arid and semi-arid regions is that the soil moisture is rarely 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, whereas after a long dry period, the effect of evapo-transpiration from the vegetation is minimal.

Lange et al. (2003) investigated the potential recharge in semi-arid areas by undertaking sprinkler tests in a study area near Natuf area. It showed that no runoff is generated from rainfall over dry soil until a certain amount of rainfall is exceeded. This contradicts 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.

In this method, the effective precipitation (EP) is calculated as the difference between rainfall and potential evaporation. If EP is positive, the rainfall value is larger that 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 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 (-)

The steps required to undertake the WT method are outlined below and are presented as a flowchart in Figure 11.

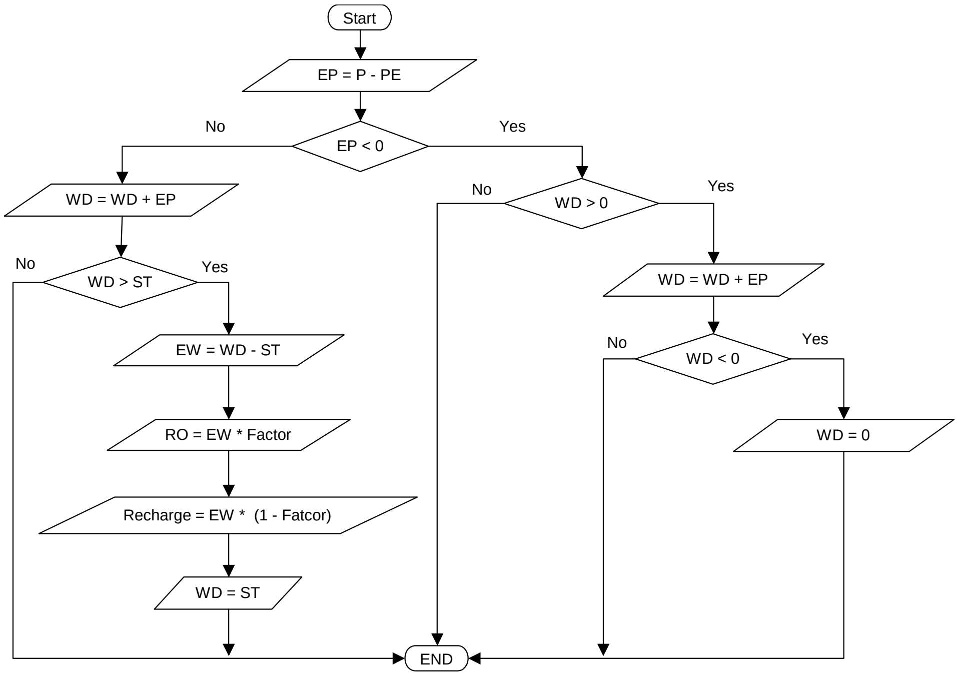


Figure 11 Flow chart for the proposed method of recharge calculation

3.2.3 Urban areas recharge calculation method

Urbanisation affects recharge through leakage of water to supply and drainage of waste water. Rainfall recharge is, however, decreased due to hardstanding and roofs diverting rainwater to drains. All engineering practices aim to minimise the leakage from sewers; however, age, lack of maintenance and unforeseen factors such as unexpected extra road loads may lead to cracks in sewers.

During the construction of the model objects, the model overwrites the construction of an SMD or WT recharge node type by an urban area recharge node type when required. The framework of recharge calculation in urbanised areas is illustrated in Figure 12 and is summarised as follows. First, 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. Two sources of water are identified in this case. The first is recharge from pressurised water mains (PWM) and sewers that is calculated as a percentage of the daily water supplied to the area. The second is recharge from the grassed part and based on the application of the 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 factorised by the percentage of the area of the green part to the total urban area and added to the recharge resulting from PWM and sewer leakage. 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. However, the topographical characteristics of the area play an important role in determining the storm water pipe discharge location. In the current recharge model, only one storm water discharge point is associated with each urban area. It is assumed that if more than one discharging location exists, the urban area is divided into sub-areas the number of which is equal to the number of storm water pipe outlets.

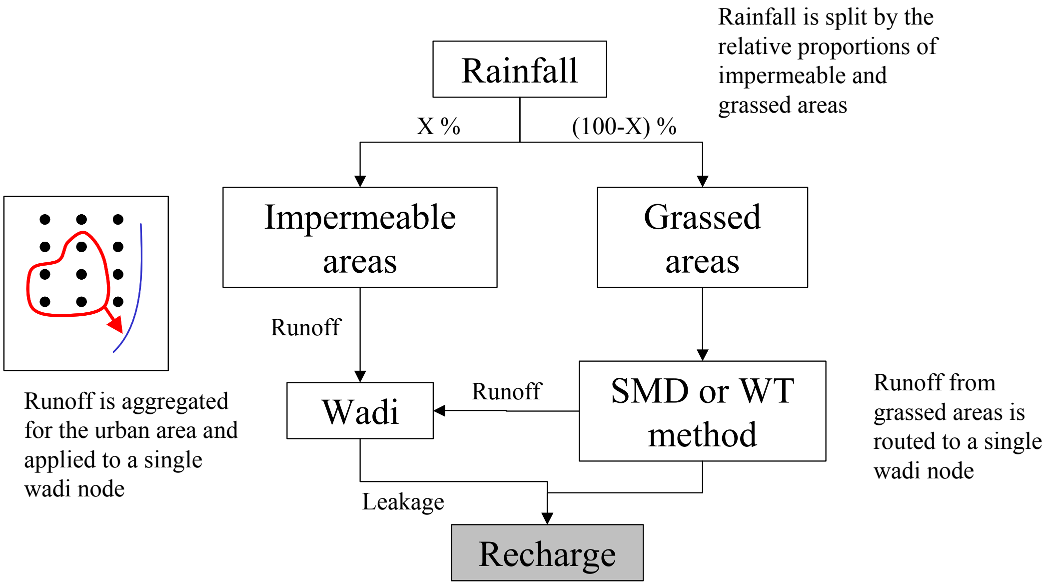


Figure 12 Framework for recharge calculation in urbanised areas.

3.2.4 Irrigated areas recharge calculation method

Irrigated nodes are SMD type recharge nodes which receive, in addition to rainfall during the wet season, a specified quantity of water during the dry season. Unlike the SMD recharge nodes, there is only one landuse type with constant values of root constant (C) and wilting point (D) associated with each irrigated area. 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 part is the runoff and the second is water lost to the fields. This first part is routed to the nearest wadi node based on the aspect direction map of the studied irrigated area. The SMD recharge process, that includes the effect of evaporation and evapo-transpiration, is then applied to the second part to calculate the amount of water that infiltrates to the unsaturated zone.

Previous studies, McKenzie et al. (2001) for example, state that the effect of terracing for agricultural purposes on the groundwater infiltration is more significant than the effect of irrigation in the West Bank area. This is because terracing inhibits runoff and leads to an increase in the rate of water percolation while irrigation is applied to limited areas only. The recharge model can represent the effect of terracing by reducing the runoff coefficient at the terraced areas.

3.2.5 Routing to wadis

The topography of the West Bank is hilly with relatively steep gradients and is subjected to storms with high rainfall intensity and short duration. This leads to runoff that is concentrating in wadis which only flow for short periods of time. Field observations in the West Bank area confirm that flow is lost to groundwater. Wadis are, therefore, implemented in the model to take wadi losses into consideration.

The amount of flow in the wadi branches is partly controlled by the runoff coefficient that is allocated to the recharge nodes. This coefficient represents the percentage of the excess water found at each recharge node to be routed to the wadi. The routing procedure is based on an aspect map created in the GIS environment. This map indicates the direction of the inclination of the ground surface at each recharge node and the runoff water is moved from one recharge node to another until a wadi node is reached. The flow at the wadi node is then incremented by the amount of the runoff flow. It is assumed that when a runoff flow, which is generated at one recharge node, flows over another recharge node, the water content of the soil increases at this node. This flow diminishes in quantity before moving to the next recharge node.

An overland loss factor also influences the wadi flows and is defined as the percentage of the runoff water generated from one node and lost over another. This is referred to in the model as the runon factor and is set in a more sophisticated way than the runoff factor. It is assumed that this factor depends on the physical characteristics of the rocks over which the water is moving and it is defined as the loss of water per metre length. Water loss is, therefore, dependent on the travel distance. Because there is a possibility of one node to receive runon water from more than one recharge node, the runon water at the considered node is incremented each time Runoff water overpasses it within one time step. The total runon flow of a node, however, is considered on the next timestep (i.e. the next day) and the amount of water accumulated due to runoff from other nodes is then added to the rainfall amount at this timestep.

3.2.6 Springs

Springs occur where the water table intersects the ground surface. The groundwater head differences within the aquifer enable the groundwater flow to move horizontally as well as vertically. The groundwater travel time to springs is dependent on the groundwater head difference, the distance between the location of the source water and the spring and the hydraulic conductivity of the aquifer. 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. This is, however, out of the scope of this study and alternatives approaches to represent springs have had to be found.

It is assumed that a part of the recharge flow that reaches an unsaturated node connected to a spring moves horizontally and discharges to the wadi through the spring. Springs are represented in the model as objects that are connected to the Unsaturated node objects. This connection is based on the following five conditions:

- 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 elevations.
- The spring connects only with Unsaturated nodes that are located in the outcrops of the geological strata pre-specified at the spring.
- There is no topographical depression between the spring node and the recharge node that is lower than the spring elevation.
- The Unsaturated node falls within an area with a specified diameter. This limits the connection of the springs to nodes that satisfy the above three conditions but are separated with great distances from the springs.
- 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.

If there is a possibility for an Unsaturated node that satisfies the above conditions corresponding to two different springs, the node connects to the nearest spring.

3.3 DATA REQUIREMENTS

The recharge model is data intense. Calculation grids are specified for the recharge model; a base grid and then any number of refined grids are required in order to calculate recharge on a distributed basis using a daily time step.

The user has to specify the start and end time of the model simulation. In addition, the distribution of nodes required for the calculation has to be specified. This is done using an array of ones and zeros to determine which nodes are to be included in the recharge calculation. Time series output of monthly recharge can also be produced at specified locations.

The data used for the model includes:

- Rainfall – daily rainfall either in the form of Theissen polygons for selected raingauges and gridded long-term average (LTA) rainfall or gridded rainfall values.
- Potential Evaporation – monthly evaporation and Theissen polygons for selected meteorological stations and gridded LTA evaporation.
- Landuse – gridded landuse distribution and associated files that give the monthly values of the root constant, the wilting point and the wetting threshold values for each landuse type.
- Runoff – gridded spatial distribution of geology types and associated files that give the monthly runoff coefficient values for each geology type.
- Topography – gridded spatial information of ground elevations.
- Aspect directions – gridded spatial information of aspect directions.
- Springs – file that gives the number of springs and their coordinates. Additional files, one for each spring, specify the groundwater velocity and the type of formation linked to springs.
- Wadi – data file that specifies the number of wadis and the coordinates of their discharging nodes. This file also gives the number of stations at which wadi flows are recorded and finally it specifies the wadi loss values based on the outcrops of geological strata.

Typically, the data that the recharge calculation requires are distributed both spatially and with time. The GIS environment allows a straightforward preparation of all spatially distributed data required by the model except for evaporation and rainfall data.

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.

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

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.

A detailed explanation of the required data files can be found in Mansour and Hughes (2005).

3.4 OUTPUT FILES

The recharge model calculates recharge on a daily basis. Regional groundwater flow models are normally run on a monthly timestep, so the output from the recharge model is produced on a monthly basis to reduce the size of the output files. Four types of output file are produced by the model:

1. Main output file – rech.out
2. Dynamic balance file – rech.db
3. Monthly recharge file – rech.tv
4. Monthly time series at the required locations as specified in rechhydro.dat – rech.ts

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

- Echoing grid setup
- Monthly recharge for each grid for both lagged and unlagged recharge
- Summaries of monthly recharge for each class of geological characteristics as specified in unsatgrid.dat
- LTA recharge for each grid as arrays and xyz format

The model calculates monthly recharge for the simulation period and is written to rech.tv. The monthly recharge is used to calculate a dynamic balance recharge for the period simulated. The dynamic balance consists of a repeated annual pattern of monthly recharge and is written to the file rech.db. The dynamic balance and monthly recharge output are formatted so that they can read directly by ZOOMQ3D (Jackson, 2001). The recharge calculation has to be performed for each grid that is used in ZOOMQ3D to enable complete consistency.

Stream flows calculated at the specified gauging stations are produced on a daily basis in a file called gauging.out. Daily flows of each spring are given in files called flowatspring##.dat where ## is the spring number. Finally, to check the water balance, the model produces a file, called dailywb.out, that reflects the daily values of total rainfall, actual evaporation, runoff, runon, water recovered from soil and recharge at all nodes of the area.

Two DXF files are also produced by the model. The first file includes a three-dimensional representation of the grid, the wadis and the connections between the recharge nodes and wadis. The second file shows the path line followed by the surface water from its origin to stream nodes or to ponds.

4 Application of the Recharge Model to the Natuf Catchment

4.1 INTRODUCTION

The scale of Wadi Natuf area allows the inclusion of all the known flow processes to be incorporated. These flow processes, however, depend on parameters that represent the physical characteristics of the area and that have to be determined using mathematical models in conjunction with field investigations and field experiments. The runoff coefficient, overland loss coefficient, water losses from streambeds, the average travel groundwater velocity, etc. are examples of the parameters that influence the recharge results. The values of these parameters can be estimated, at this stage, by carefully studying the available topographical and geological maps. In this section, the variation of the values of these parameters and their implications on the recharge results, wadi flows and spring flows are examined. Parameter values that produce results consistent with the field observations are then selected and included in the Wadi Natuf recharge model.

The Natuf area streams are assumed to follow the typical ephemeral type of surface water found in arid and semi-arid areas. These types of rivers flow only in response to storms and this is consistent with the description provided by the field reports. Two assumptions are made: First, wadi flows will be generated if the intensity of rainfall recorded in one day is large enough to compensate for the evaporation occurring at that day and to bring the soil moisture level within the soil to a certain limit. Second, the time required for flow to move from the most remote upstream node to the downstream wadi-discharging node, the time of concentration, is less than one day. It is also assumed that flow generated from one storm or from a sequence of storms in one day will leave the catchment on the same day.

4.2 DATA REQUIREMENTS

A 200 m square cells grid is used to represent the study area in the recharge model (Figure 13). The selection of the cell size is based on a compromise between the accuracy of the representation of the special features of the area such as the wadis, and the run time required by the model to produce the final results.

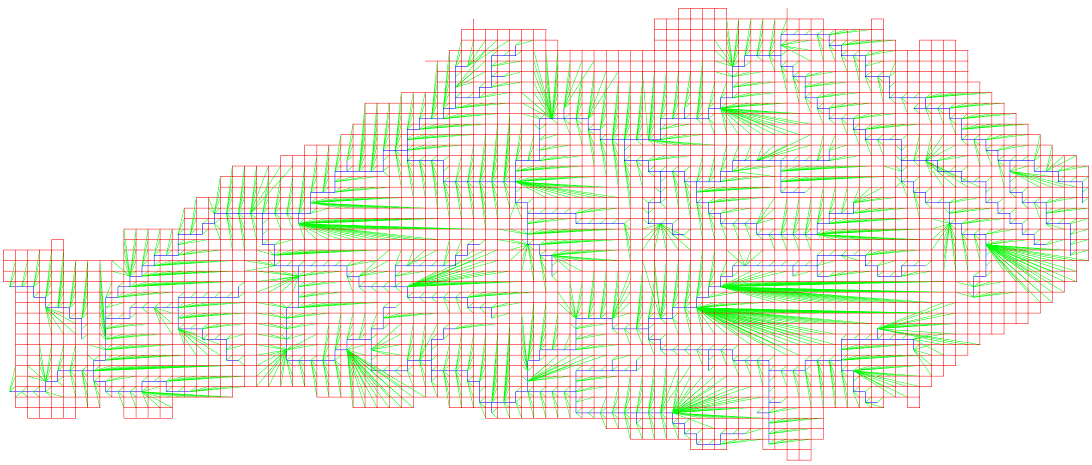


Figure 13 Model grid, wadis and runoff routing for the Wadi Natuf catchment

4.2.1 Rainfall

Daily rainfall is required by the recharge model (provided by Newcastle University) as grid files exported from Arcview for the whole of the West Bank. Each grid represents one rainday, if precipitation occurs. The data are imported into the model and the rainfall for the Wadi Natuf area is then used for the recharge calculation.

4.2.2 Potential Evaporation

The recharge model requires monthly potential evaporation (PE) data. Average monthly PE has been provided for the six meterological stations in the West Bank. The nearest, and most climatically similar, meterological station to Ramallah is Hebron (Table 5). The Monthly PE data for the Wadi Natuf is, therefore, obtained by factoring the monthly data at Hebron by the ratio of the long term averages at each location.

Table 5 Monthly PE for Hebron and Ramallah

	Monthly PE (mm month^{-1})	
	Hebron	**Ramallah**
January	68.1	70.5
February	64.4	66.6
March	82.2	85.1
April	149.1	154.3
May	176.8	182.9
June	232.5	240.6
July	280	289.7
August	217	224.5
September	175.9	182.0
October	123.4	127.7
November	138.2	143.0
December	80.8	83.6
Total	1788.4	1850.4

4.2.3 Landuse and applicability of SMD

Outside the urbanised areas, Palestinian villages and Israeli settlements, the majority of the landuse is made up of three main types (Figure 14):

- Natural grassland
- Agricultural land with natural vegetation
- Olive tree plantations

These three landuse types are evenly distributed over the Natuf catchment. Examining the photos accompanying the various field trip reports undertaken by the SUSMAQ team shows that, apart from valley floors, there is limited soil cover in the catchment. The lack of good soil coverage means it is unlikely that soil based recharge processes will be operating. While terracing activity is hard to trace and to represent in the model, the impact of olive grove areas is included in the model by reducing the runoff coefficient inhibiting runoff at the nodes representing these areas.

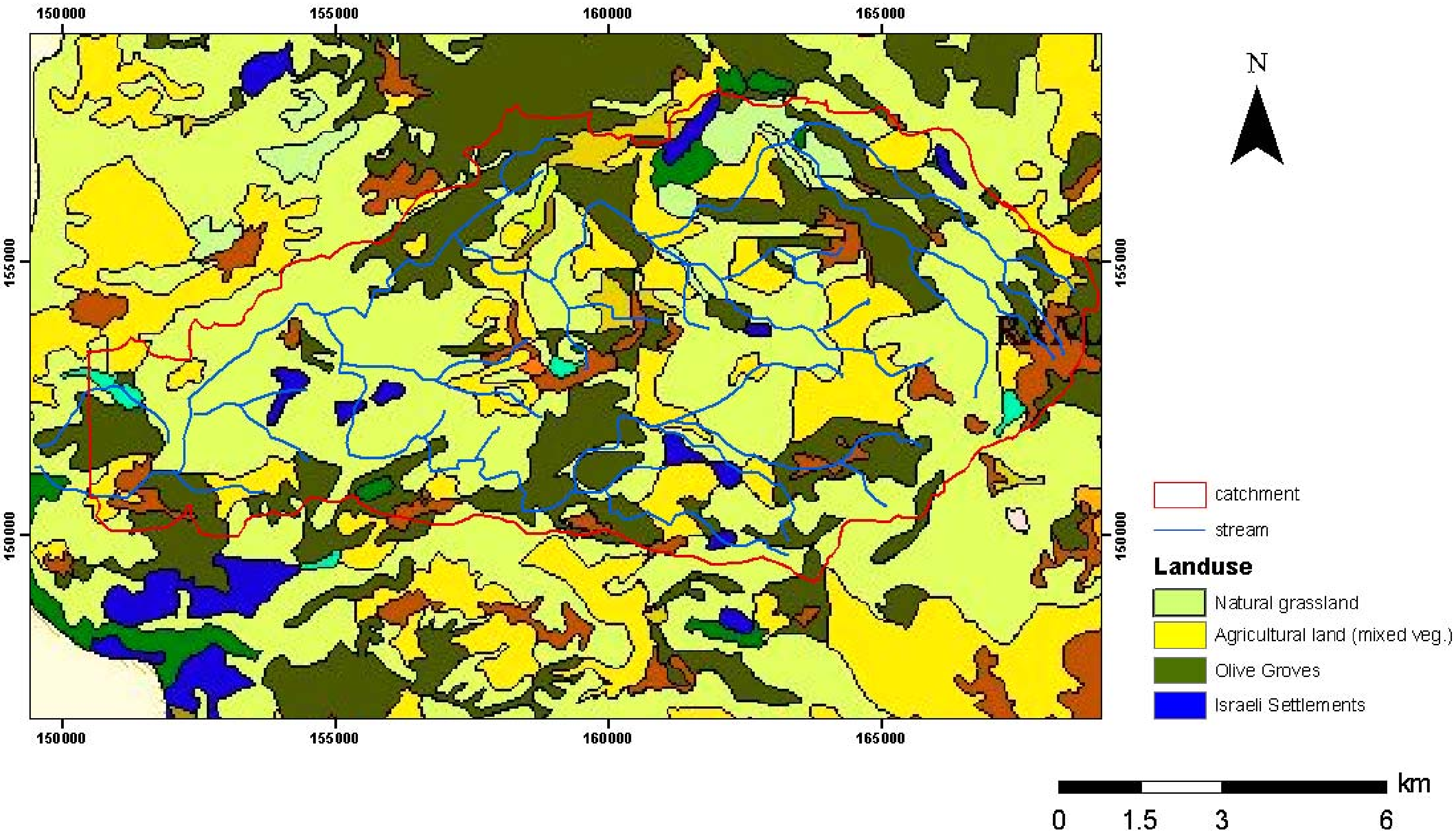


Figure 14 Landuse for the Natuf catchment

4.2.4 Springs and their location

In all, over 100 springs have been identified in the Wadi Natuf catchment. These springs can be classified into three basic types:

1. Springs that originate from junction of Lower Beit Kahil and the Yatta formation.
2. Springs that originate from the top of catchment – Qatana.
3. Springs issuing from layers of alternating marl and limestone bands – Soreq.

Of the springs issuing from the Lower Beit Kahil, six major spring groups have been identified. In the recharge model, each group is concentrated at one point (for the locations see Table 6). The total flow from all the springs has been estimated at 0.5 $Mm^3\ a^{-1}$ (1400 $m^3\ d^{-1}$) (Messerschmid, 2003). Of this total flow, it is assumed that approximately half can be attributed to the group of springs around Beitillu. Figure 15 illustrates the location of the identified spring groups.

Springs are connected to the unsaturated nodes based on the respective ground elevation at these nodes and the ground elevation where the spring originates. In addition, the model includes a maximum distance that controls this connection. Spring nodes separated from unsaturated nodes by distances larger than the specified maximum do not connect to each other even if other connecting criteria are satisfied. This distance is set, in this study, to a value of 5000 m. Two values of the groundwater velocity, which determines the travel time of percolating water to reach the springs, are considered in two separate runs to examine the effect of the value of this velocity on the recharge values and the spring flow behaviour.

Table 6 Main spring groups in the Wadi Natuf

Name	X	Y	Elevation (m asl)
Wadi Zarqa	159000	155000	324.0
Beitillu	161000	154000	523.2
Jammala	159500	153500	432.3
Ras Karkar	161000	150000	528.6
Kobar	165000	155000	~570.0
Anu Skhedem	166000	152000	~700.0

4.2.5 Runoff routing

Each wadi node has an associated set of nodes from which it receives runoff. The model links up wadi nodes with the appropriate recharge nodes based on a map of aspect directions,. Runoff generated from these recharge nodes is then routed to the wadis.

Two variables control the generation of runoff and its loss as it is routed to the wadis. Firstly, a runoff coefficient is designated which, controls the proportion of rainfall that contributes to runoff at a recharge node. Secondly, the overland loss coefficient, which determines the amount of overland runoff lost per metre at each node, is specified. Currently the runoff coefficient is set to 60% at all nodes except at those representing the olive groves where it is reduced to a value of 30%. The overland loss coefficient is set to 0.0005 m^{-1}. This value leads, in the case of a 200 m square node, to 1% of the water over passing a node to be lost at that node.

4.2.6 Wadi Losses

The current conceptual model of infiltration from losses of flow from wadi beds is that losses from wadis occur on every geological formation, with the exception of the Yatta. Field trips have identified wadis flowing over the Yatta and flow dissapearing downstream once the wadi flows over the Hebron formation. Therefore, no losses are allowed from the wadi when it is in contact with the Yatta. A loss coefficient is specified for all other geological outcrops. The effect of including this factor on the resulting stream flows and recharge results is investigated by considering three separate runs with wadi losses of 0.0, 0.01 and 0.05.

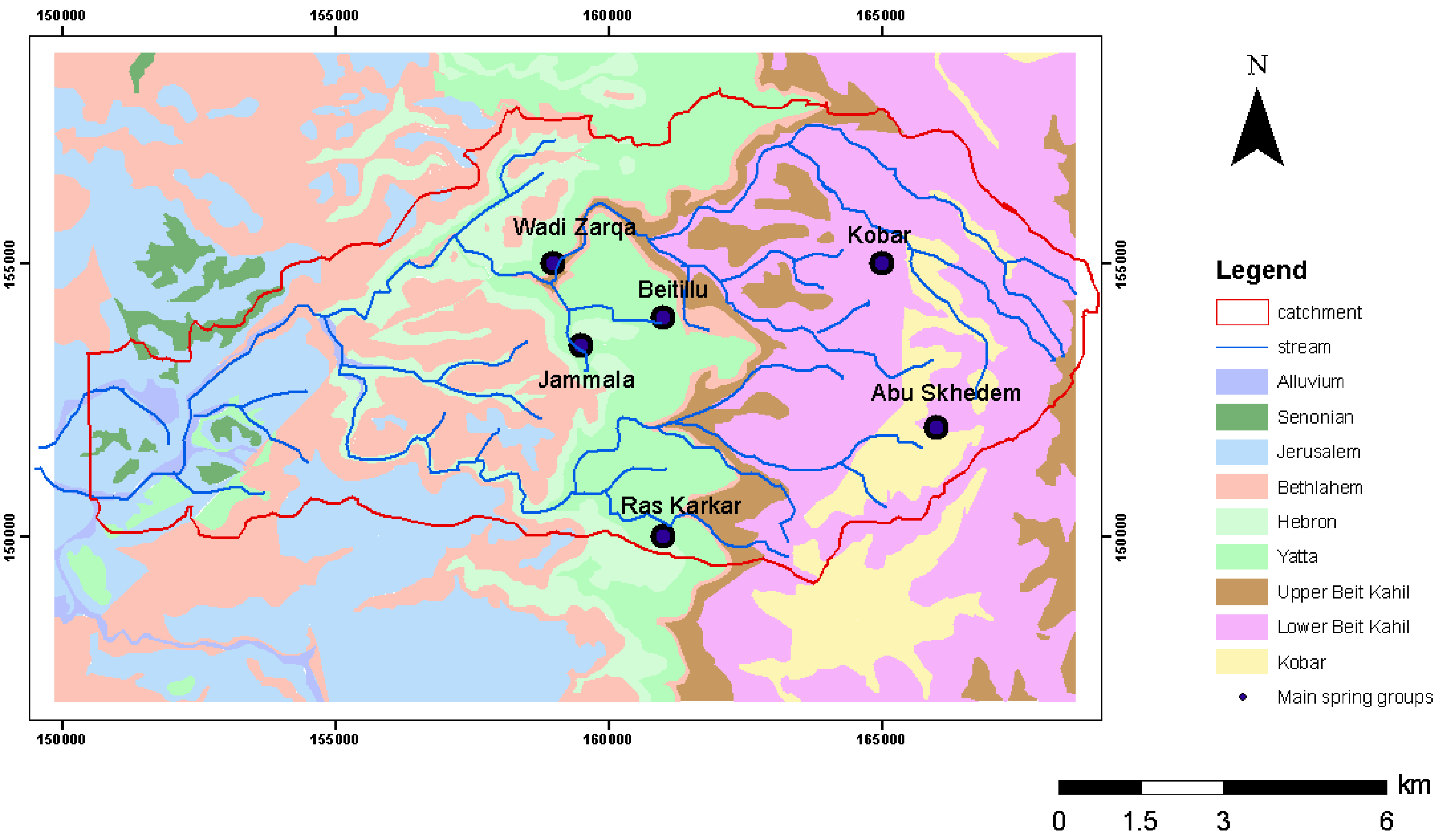


Figure 15 Location of main spring groups in Wadi Natuf

4.3 MODEL RESULTS

4.3.1 Introduction to modelling

Two sets of simulations were undertaken using the recharge model developed for the Wadi Natuf. The two series of simulations were from January 1990 to December 1996 and winter 2003/4. The former was undertaken with rainfall data provided by Newcastle University for the SUSMAQ project and the latter used the data collected from the Wadi Natuf catchment during the winter of 2003/4. These data were collected by the SUSMAQ team based in Ramallah. However, the information was incomplete and a full analysis could not be undertaken on the data collected over the winter, therefore, a series of runs were undertaken to demonstrate the potential recharge mechanisms operating in the Wadi Natuf.

4.3.2 Simulation from January 1990 to December 1996

Six separate runs that reflect the use of three different wadi loss (WL) values and two different groundwater velocities (V_{GW}) are undertaken to investigate the effect of changing the values of these parameters on the resulting recharge values, wadi flows and spring discharges. Values of 0%, 1% and 5% are set for the wadi losses while the groundwater velocity is set to 5 m d^{-1} or 20 m d^{-1}. The runs are performed for a total period of seven years with the rainfall data prepared for the period January 1990 to December 1996.

Changing the groundwater velocity, which controls the spring flow values, did not affect the long-term average recharge results. The variation of the wadi losses from 0% to 5%, on the other hand, resulted in an increase in the recharge values by the order of 35%. The long-term average recharge results produced with the same wadi loss values and a groundwater velocity of 5 m d^{-1} are listed in Table 7.

Table 7 Long term average recharge results over Wadi Natuf (V_{GW} = 5 m d^{-1})

	WL = 0.0	**WL = 0.01**	**WL = 0.05**
Average (Mm^3 d^{-1})	0.037	0.039	0.049
Average (mm a^{-1})	151.9	162.9	206.1

The daily stream flows are monitored at the discharging point of the Natuf wadi. Figure 16 to Figure 21 show the modelled flows with a groundwater velocity of 5 m d^{-1} and 20 m d^{-1} respectively. Figure 16 to

Figure 18 represents the cases of using wadi losses of 0, 0.01 and 0.05 respectively. These plots show that, because of the relatively small spring discharges compared to the total runoff flow, the effects of varying the groundwater velocity do not greatly influence the total values of the stream flows. Figure 16 and Figure 19, Figure 17 and Figure 20 and Figure 18 and Figure 21 are very similar.

Figure 16, Figure 17, Figure 19 and Figure 20 show that the major stream flows are concentrated within the wet season of each year with maximum daily water volumes of 2.5 Mm^3 d^{-1} and 0.2 Mm^3 d^{-1} when the wadi losses are set to values of 0.0 and 0.05 respectively. The small values of stream flows monitored during the dry season and appearing clearly in Figure 20 are returned to the continuous discharges of springs to streams. It is found that if the springs are omitted from the recharge model, these flows disappear and stream flows are encountered for 25 days on average each year when wadi losses are set to 0.01 and for 18 days on average when wadi losses are set to 0.05. The maximum daily volume of water recorded at the gauging station whilst setting the wadi losses to 0.01 is approximately 1.2 Mm^3.

Field investigation indicated that the peak runoff flow at Natuf wadi is approximately 110 m^3 sec^{-1}. This flow may have resulted from a storm that lasted for several hours only and which may have been followed by another storm on the same day. It may not be accurate, therefore, to compare the flow generated from this storm to the maximum daily volume of water produced by the model and recorded at the gauging station. However, the comparison holds true if the daily rainfall data used in the model are resulting from one storm which occurred on that day.

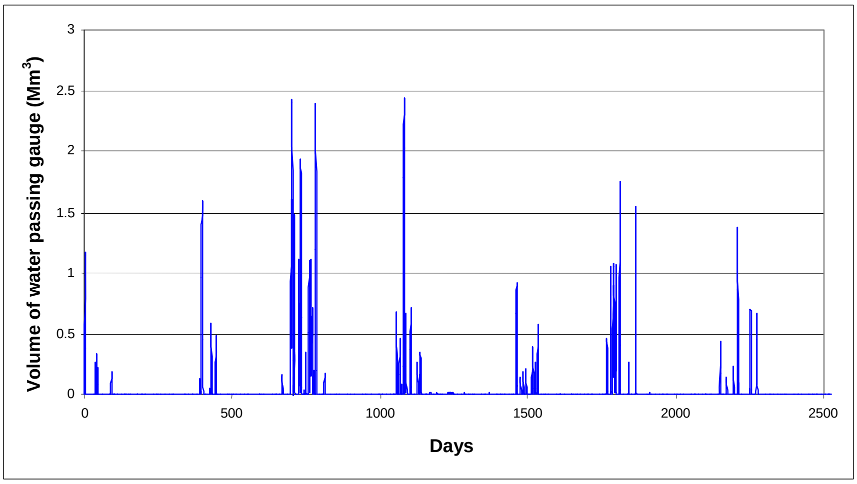


Figure 16 Stream flows with wadi losses equal to 0.0 and groundwater velocity of 5 m d^{-1}

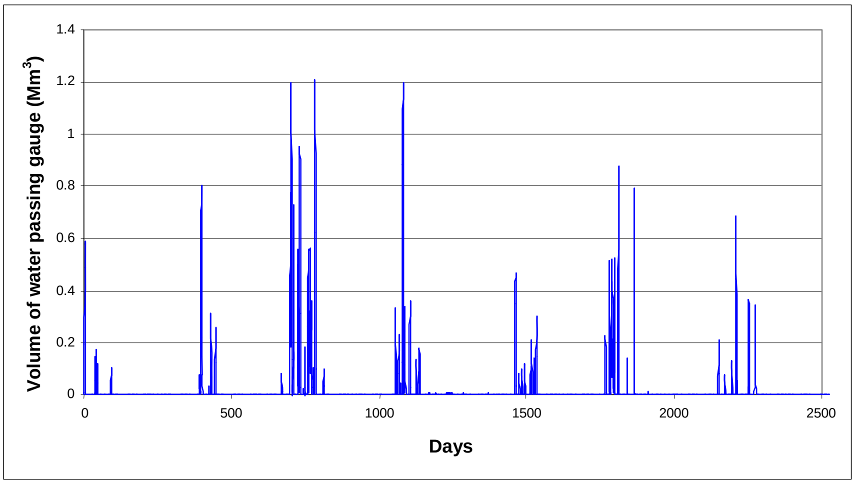


Figure 17 Stream flows with wadi losses equal to 0.01 and groundwater velocity of 5 m d^{-1}

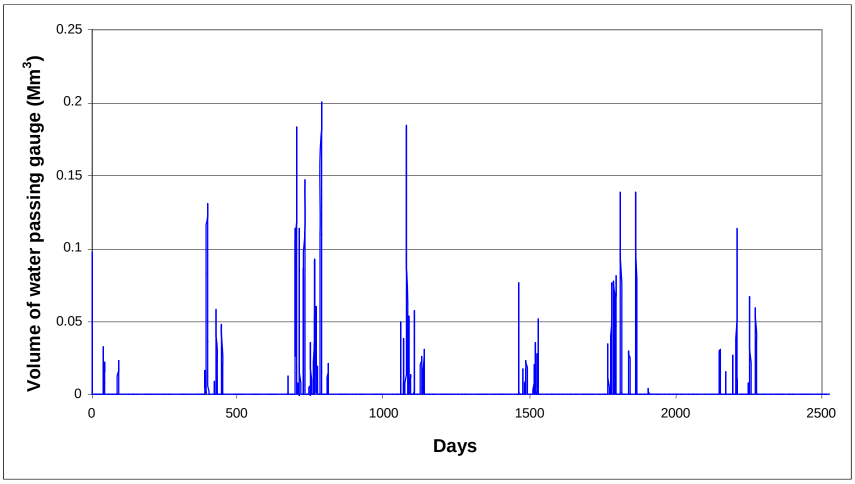


Figure 18 Stream flows with wadi losses equal to 0.05 and groundwater velocity of 5 m d^{-1}

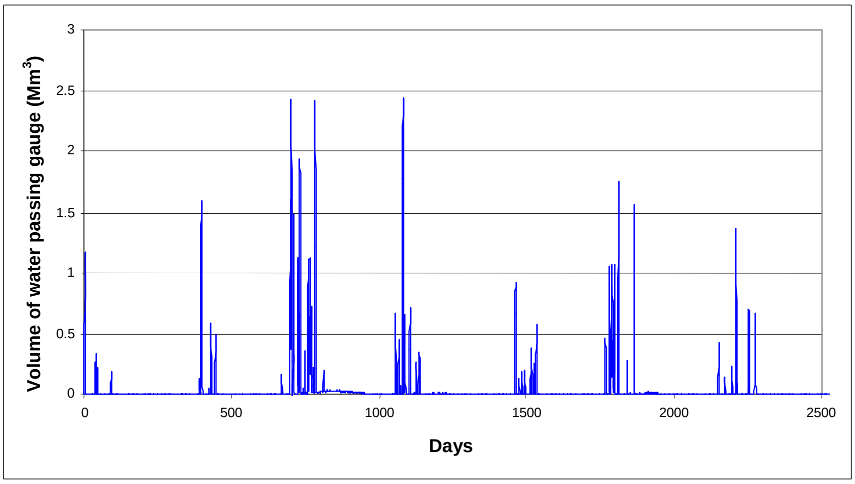


Figure 19 Stream flows with wadi losses equal to 0.0 and groundwater velocity of 20 m d^{-1}

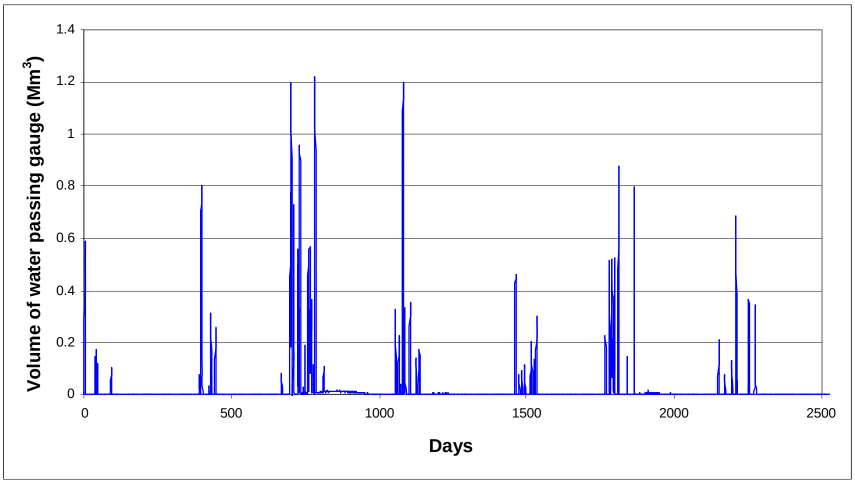


Figure 20 Stream flows with wadi losses equal to 0.01 and groundwater velocity of 20 m d^{-1}

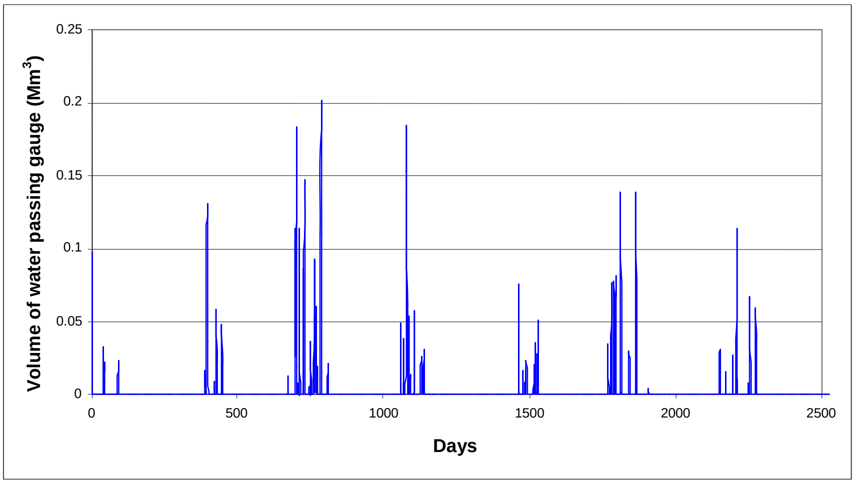


Figure 21 Stream flows with wadi losses equal to 0.05 and groundwater velocity of 20 m d^{-1}

The volume of water resulting from a given storm can be determined by constructing the hydrograph. A D-hour synthetic hydrograph from the SCS, USA is used for this purpose. This hydrograph takes a triangular shape and depends on the catchment characteristics to calculate the different parameters such as the time to peak, the peak flow and the time base. The hydrograph used in this study is described by Chadwick and Morfett (1986) and is detailed in Appendix 2. Conventionally, the peak runoff flow is determined from an empirical formula that depends on the time of concentration and the rainfall intensity. Conversely, the rainfall intensity of the storm that yields the required peak runoff is calculated from this formula.

It is found that a precipitation of 12.6 mm is required to fall continuously for a duration of 30 minutes to produce a peak runoff of 110 m^3 d^{-1}. The peak time and the base time of the hydrograph are calculated as 128 and 343 minutes respectively. This produces a total volume of water equal to 1.13 Mm^3. This volume of water is much larger than the maximum recorded stream flow with wadi losses set to a value of 0.05 and suggests that the use of wadi losses of 0.05 is wrong. This volume, on the other hand, is very close to the stream flow recorded when the wadi losses are set to a value of 0.01 and is half as much as the stream flow with wadi losses of 0.0. This indicates that the wadi loss values range from 0.0 to 0.01.

Spring flow depends on the number of nodes connected to the spring, the groundwater velocity and the percentage of the infiltrating water that is assumed to move laterally towards the spring in the aquifer. The number of nodes connected to each spring is determined automatically by the model based on the geology at the recharge nodes and the specified extent of the area influenced by the spring. Spring flows are investigated by considering two groundwater velocity values. In both cases, it is assumed that 50% of the recharge calculated at the saturated nodes, and that are connected to springs, is transferred to these springs. Since stream flow routing is the last flow process operation to be considered at each daily time step, water infiltration caused by water losses from wadi floors has no effect on spring flows. The effect of changing the values of the wadi losses are not, therefore discussed here.

Figure 22 and Figure 23 show the results of two runs corresponding to groundwater velocities of 5 m d^{-1} and 20 m d^{-1} respectively at the six spring groups. Figure 22 shows continuous spring discharges stretching over the whole considered period, while the spring discharges shown in Figure 23 dry up during certain period of times but are characterised by larger peak flow values than those shown in Figure 22. Springs, in both runs, keep flowing for a period of time that stretches beyond seven years. Springs stop flowing on 18 August 1998 when a groundwater velocity of 20 m d^{-1} is considered and on 5 September 1999 when a groundwater velocity of 5 m d^{-1} is considered. The total calculated water volume in both cases is equal to 0.0146 Mm^3. The average daily spring flow is found to be equal to 2.05 Mm^3 a^{-1} and 1.87 Mm^3 a^{-1} for G_{VW} = 20 m d^{-1} and G_{VW} = 5 m d^{-1} respectively. Continuously running springs and intermittent springs can be identified and the hydraulic conductivity of each spring can be set accordingly based on the site observations. It should be noted that the average spring flow is in the order of 0.5 Mm^3 a^{-1}. This suggests that either the recharge quantity calculated at the recharge node is too large, the considered groundwater velocity is wrong or the linking of half of the recharge value at the nodes to springs as spring flow is not realistic.

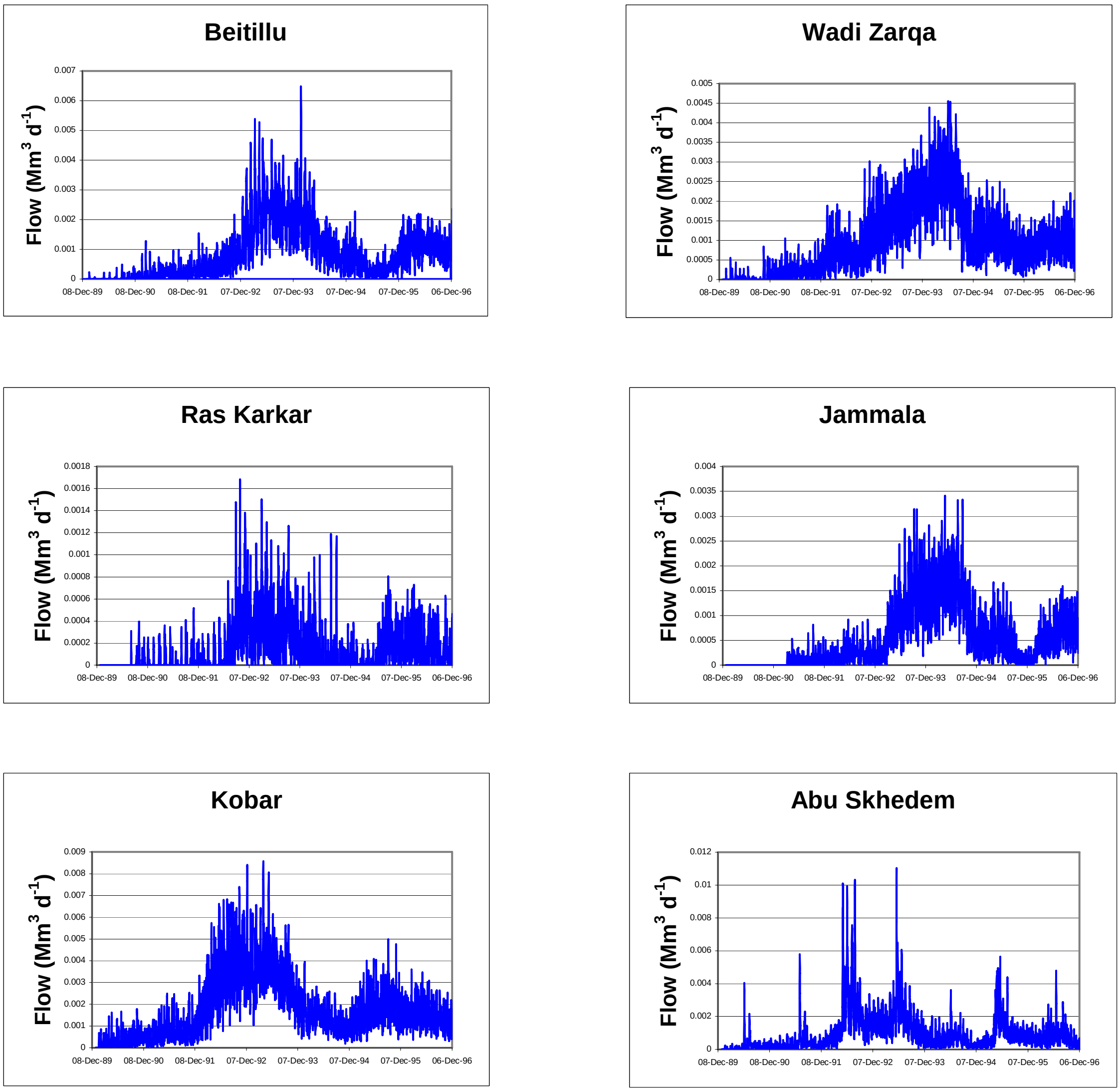


Figure 22 Stream flows with wadi losses equal to 0.05 and groundwater velocity of 20 m d^{-1}

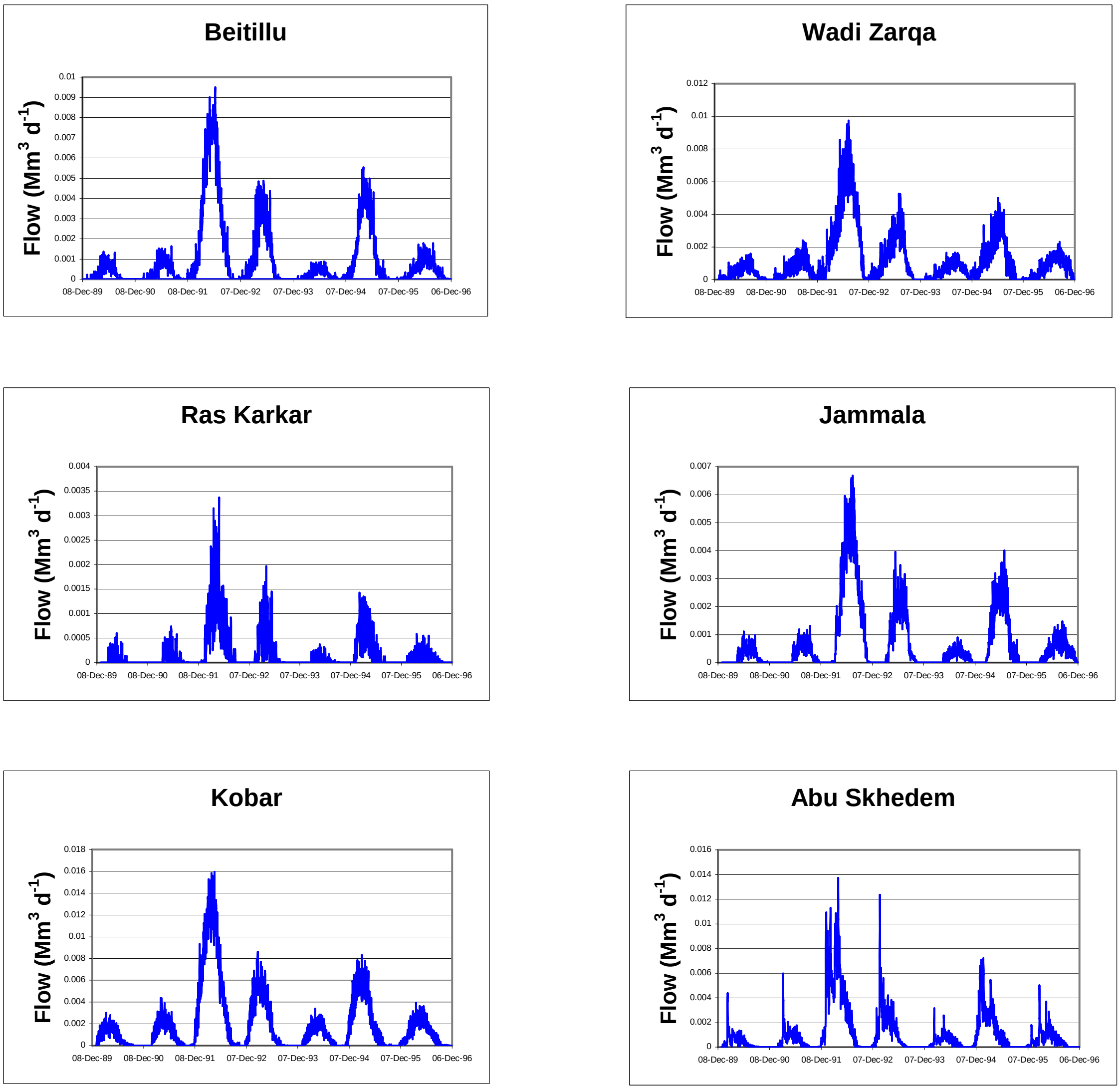


Figure 23 Stream flows with wadi losses equal to 0.05 and groundwater velocity of 20 m d^{-1}

4.3.3 Simulation of winter 2003/4

During the winter of 2003-2004 the SUSMAQ project team undertook extensive fieldwork to gather information about precipitation, potential evaporation and wadi flows. This work included setting up automatic weather stations that provided the wind speed and direction, precipitation, temperature and solar radiation accompanied with evaporation pans to determine potential evaporation and tipping buckets for rainfall. In addition, wadi flows are monitored using pressure divers and the variation of the soil moisture was monitored by installing theta probes at two sites. However, a problem lay in the interpretation of the information produced by the devices used to monitor the precipitation, evaporation and flows. These information must be compared to reference parameters, or must be converted using a mathematical equation that includes the characteristics of the used device, so that they can be translated into meaningful information. At the time of preparation of this report, these reference parameters or mathematical equations were not available and so no comprehensive comparison between the model results and field data was possible. However, the rainfall data recorded during the winter 2003/4 are used to calculate an average distribution of recharge over the Natuf area and a comparison between the behaviour of the monitored soil moisture and the model calculated soil moisture deficit and are described below.

RAINFALL DATA.

The OOBRM recharge model reads the distributed rainfall information from files that have the ArcView exported ASCII format. However, the current rainfall information are not distributed and represent rainfall values at the specific rainfall stations. The prediction data provided by Newcastle University cover the winter of 2003-2004; however, these are data prepared by projecting the historical available data into the future and cannot be used as real data. The OOBRM code is, therefore, updated so rainfall data are treated in a similar way to the evaporation data, i.e. by automatically distributing the rainfall over the study area using the point information and an average LTA distribution.

There are nine available rainfall stations both in and adjacent to the Natuf study area (Figure 24). The preparation of rainfall data involves several steps. First the average rainfall at each rain station is determined and then contour lines representing the average rainfall is created. These contour lines can be created in a GIS environment using the ArcView program. These contour lines are then gridded so each model node can be allocated an average rainfall value. Finally, Theissen polygons are prepared so that each model node can be related to a rainfall station. Rainfall at each model node is then determined by multiplying the average rainfall value at the node by the rainfall value of its related rainfall station and dividing by the average rainfall calculated at the same rainfall station. The created Theissen polygons are shown in Figure 24. Rainfall data are available for the period starting on the 18 December 2003 and ending on the 31 March 2004.

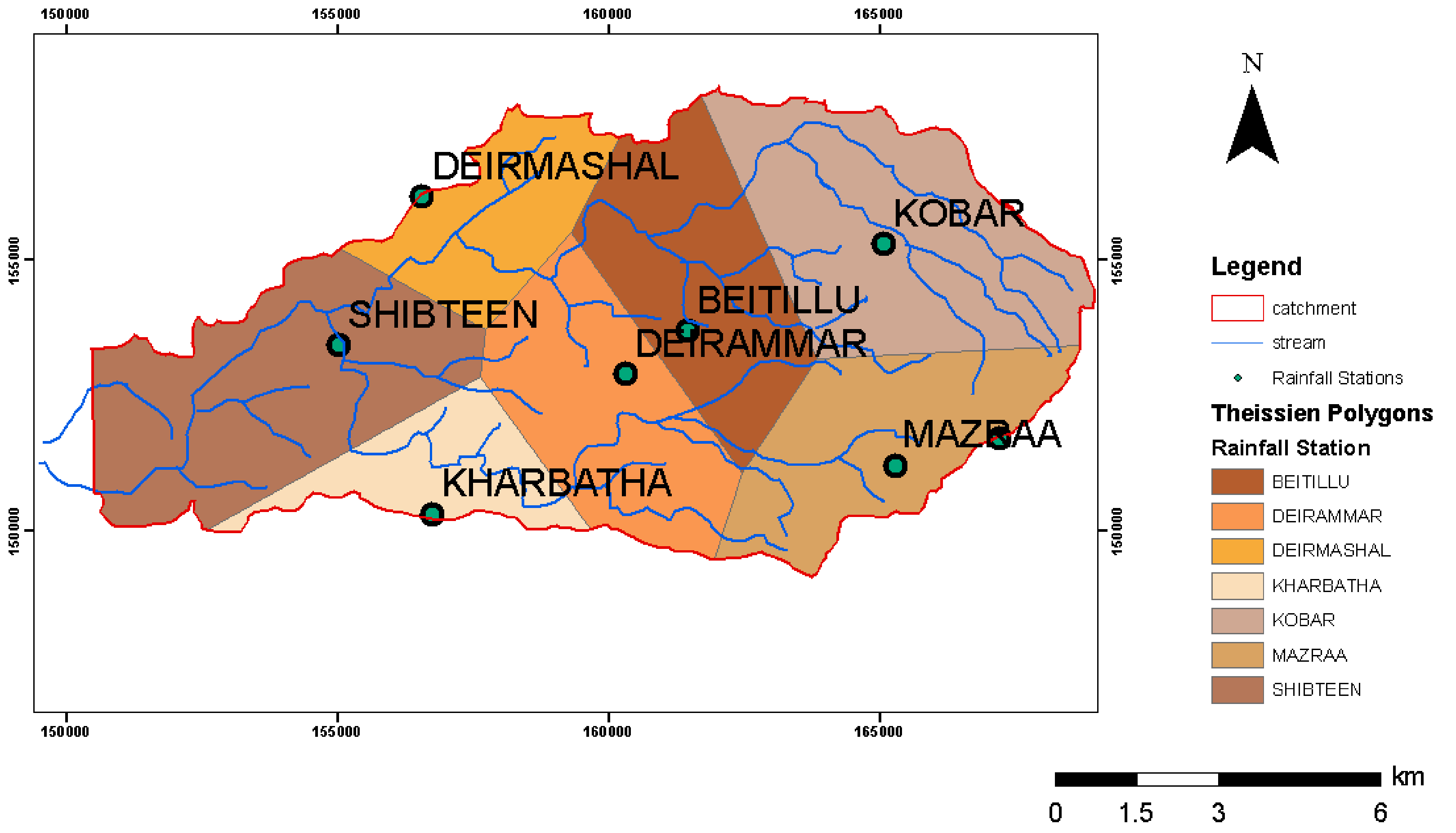


Figure 24 The rainfall stations and the corresponding Theissen polygons in Natuf area

OTHER INPUT DATA

The other model input data such as the evaporation, landuse, runoff coefficients, spring number and locations are the same as for the runs undertaken in the previous model. The values of 0.01 and 20 m d^{-1} are considered for the wadi losses and the speed of groundwater movement towards the springs respectively. Because the potential evaporation is determined from the evaporation pans by the means of divers, it was not possible to translate the field information into potential evaporation values. The potential evaporation available at Hebron Meterological station and used in the previous runs were also used in this simulation.

DISCUSSION OF RESULTS

The average recharge values are calculated using the Soil Moisture Deficit (SMD) and the Wetting Threshold (WT) calculation methods. Two simulations with two WT values, 15 and 30 mm, are considered.

Table 8 shows the simulations results in $Mm^3 d^{-1}$. As expected from the previous runs, the simulation with WT value of 15 mm produces the highest recharge value and the simulation using the SMD calculation method produces the lowest ones. However, these recharge values are approximately three times larger than the recharge values listed in Table 7. This reflects the current simulations considering the wet months only while the previous simulation considered rainfall from all seasons over several years. The calculated recharge values should be treated with caution.

Table 8 Average recharge values for winter 2003/4

	SMD method	**WT method (WT = 30 mm)**	**WT method (WT = 15 mm)**
Recharge ($Mm^3 d^{-1}$)	0.114	0.159	0.176

The main aim of this simulation, however, is to compare the variation of the calculated soil moisture deficit over time with the monitored variation of the soil moisture content. Although the modelled soil moisture deficit will increase as the observed soil moisture content decreases and vice versa. Two theta probes were installed to monitor the variation of the soil moisture contents with time at two sites in the study area. These sites are located at Shuqba and Beitillu and the location of which are shown in Figure 25.

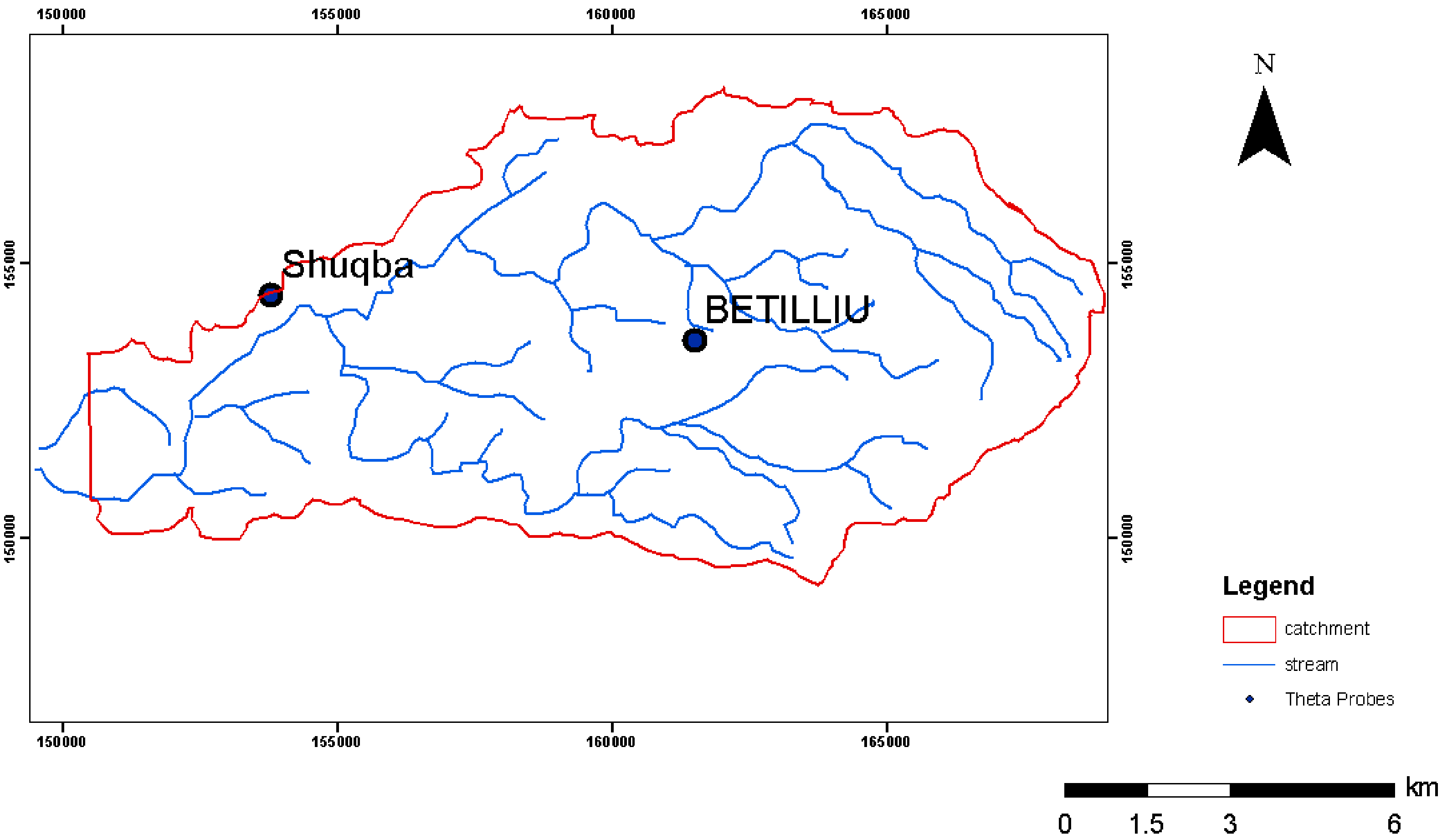


Figure 25 Location of Shuqba and Beitillu theta probes in Natuf area

The moisture content of the soil at Beitillu are monitored using three channels that are assumed to detect the soil moisture at different depths (although this is not clearly mentioned in the acquired field data and the monitoring depths are not stated). The moisture contents of the soil at Shuqba, on the other hand, are monitored using two channels. Figure 26 shows a plot of the variation of the soil moisture contents with time against the rainfall time series. This figure indicates that the moisture contents of the soil at Beitillu are higher than the moisture contents at Shuqba. However, the time series plots at the two sites show similar behaviour. A sudden increase in the moisture contents is observed when rainfall occurs and slow decrease in the moisture contents is observed during the dry period.

Figure 27 shows the time series of the soil moisture deficit recorded at two nodes of the model that represent the Beitillu and Shuqba Sites. The results shown in Figure 27 are produced using the SMD calculation method. Although the same landuse types are defined at the nodes representing these sites, Figure 27 shows that the variations of the soil moisture deficit at Betillu are lower than the variations of soil moisture deficit at Shuqba. This means that higher soil moisture contents are maintained at Beitillu than at Shuqba which is consistent with what is observed in field data. The difference in the time series at these two locations is due to the application of different daily rainfall rates and to the different considerations of runoff and runon mechanisms.

Figure 28 and Figure 29 show a comparison between the field data of the soil moisture contents and the model results of the soil moisture deficit at Beitillu and Shuqba respectively. The model results of the soil moisture deficit are plotted in reverse order along the left-hand Y axis to make the comparison easier. Since the figures show plots of two different entities, a comparison of magnitude is not possible; however, the time variant behaviour of the curves show marked similarities. These similarities may be result of both data reflecting the behaviour of the applied rainfall. The higher moisture contents of the soil at Beitillu over the soil at Shuqba, which is properly simulated by the numerical model, must, however, be highlighted.

The use of the wetting threshold recharge calculation method produces soil moisture deficit time series that are similar to those produced using the SMD calculation method. However, when the WT method time series curve indicates that the soil moisture deficit has reached the threshold limit set in the WT method the results differ. In addition, the difference between the soil moisture deficit time series at Beitillu and Shuqba is less pronounced when the WT method is used (Figure 30) than when the SMD method is used (Figure 27).

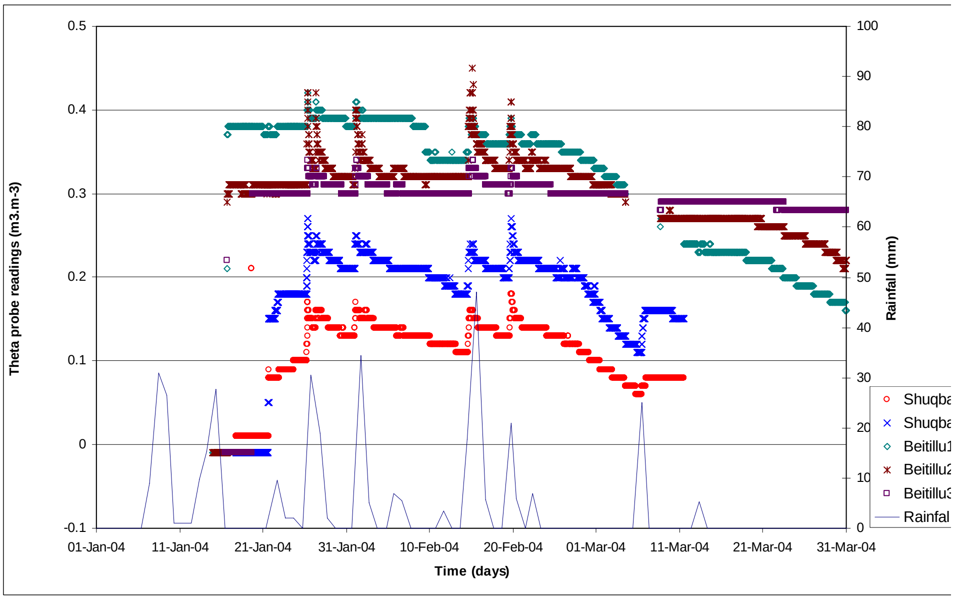


Figure 26 Theta probe results at Beitillu and Shuqba

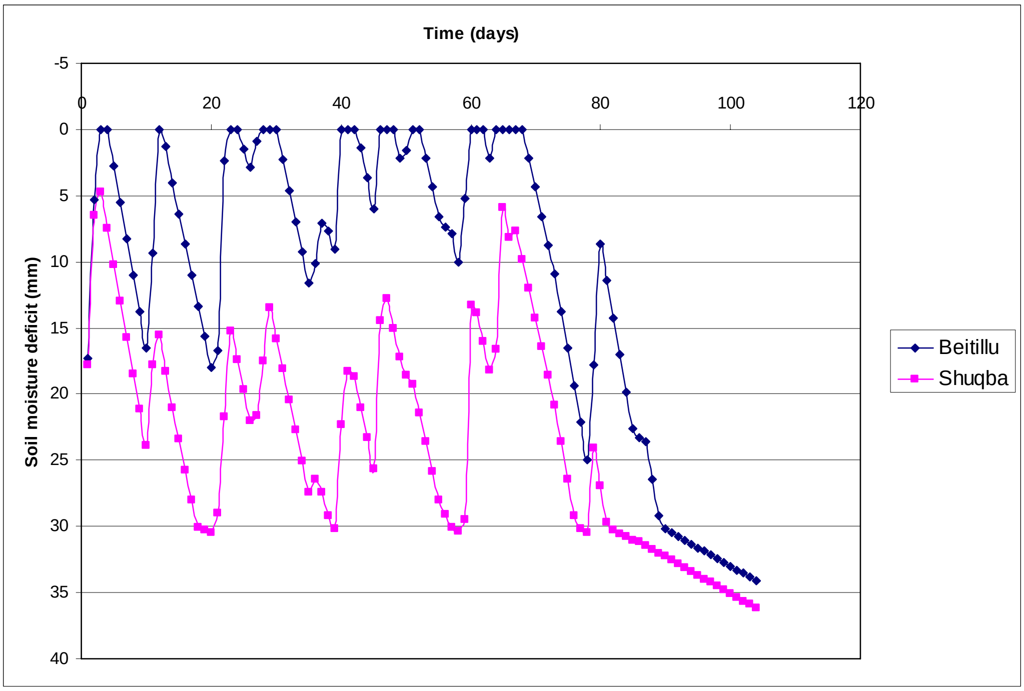


Figure 27 Numerical results of the soil moisture deficit at Beitillu and Shuqba using the SMD recharge calculation method

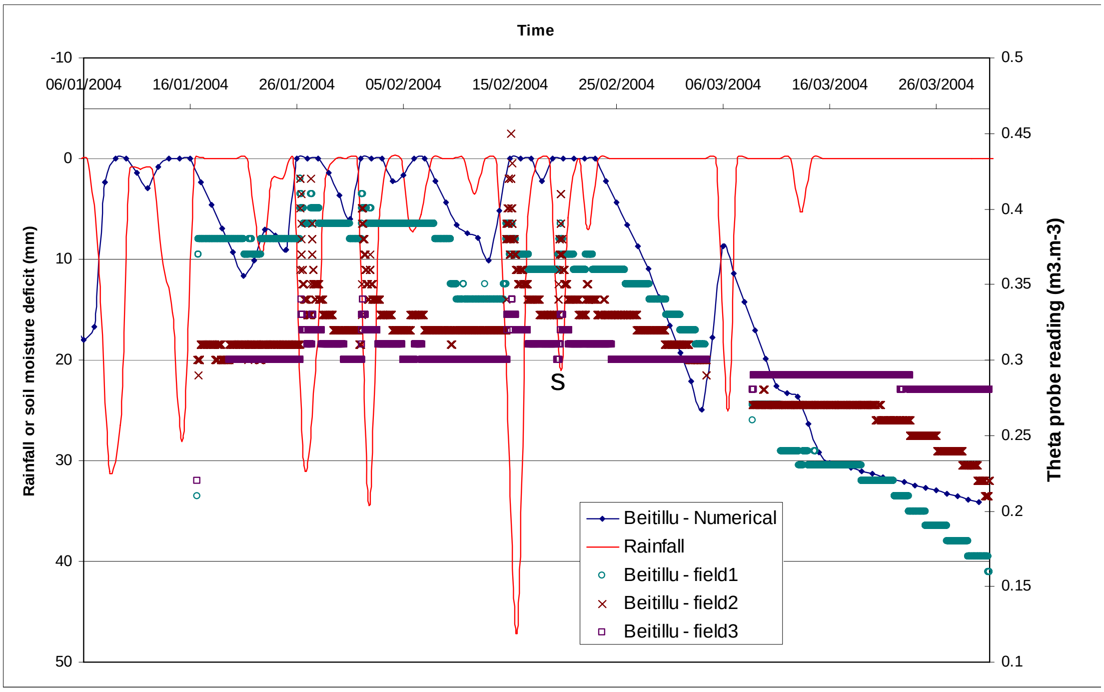


Figure 28 Comparison between the numerical soil moisture deficit and field soil moisture contents at Beitillu.

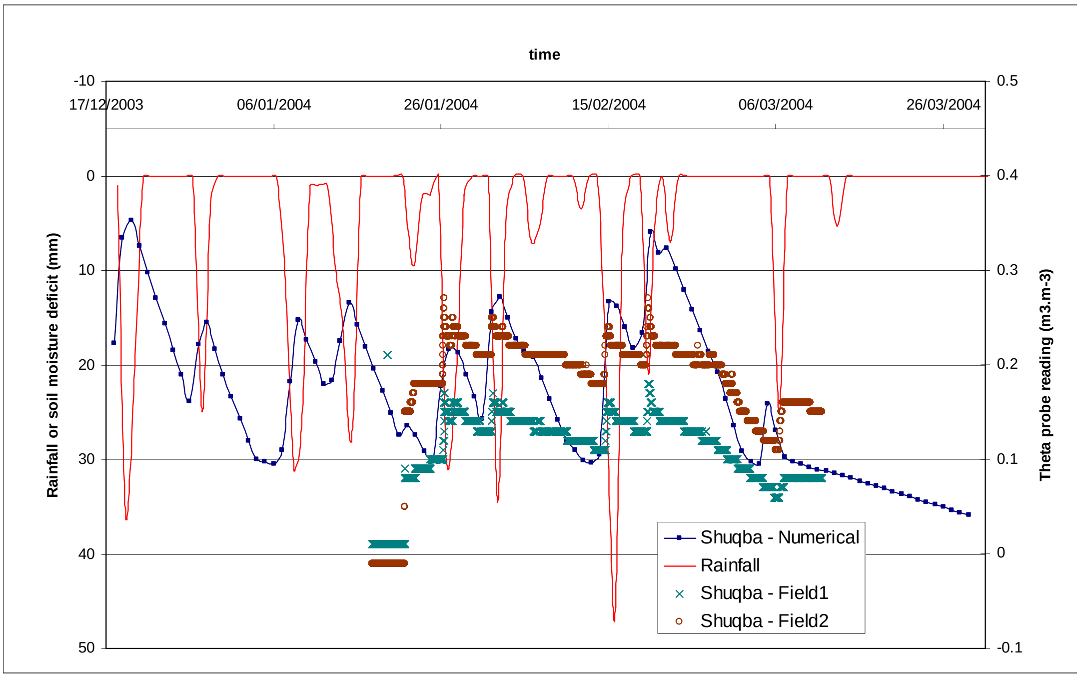


Figure 29 Comparison between the numerical soil moisture deficit and field soil moisture contents at Beitillu.

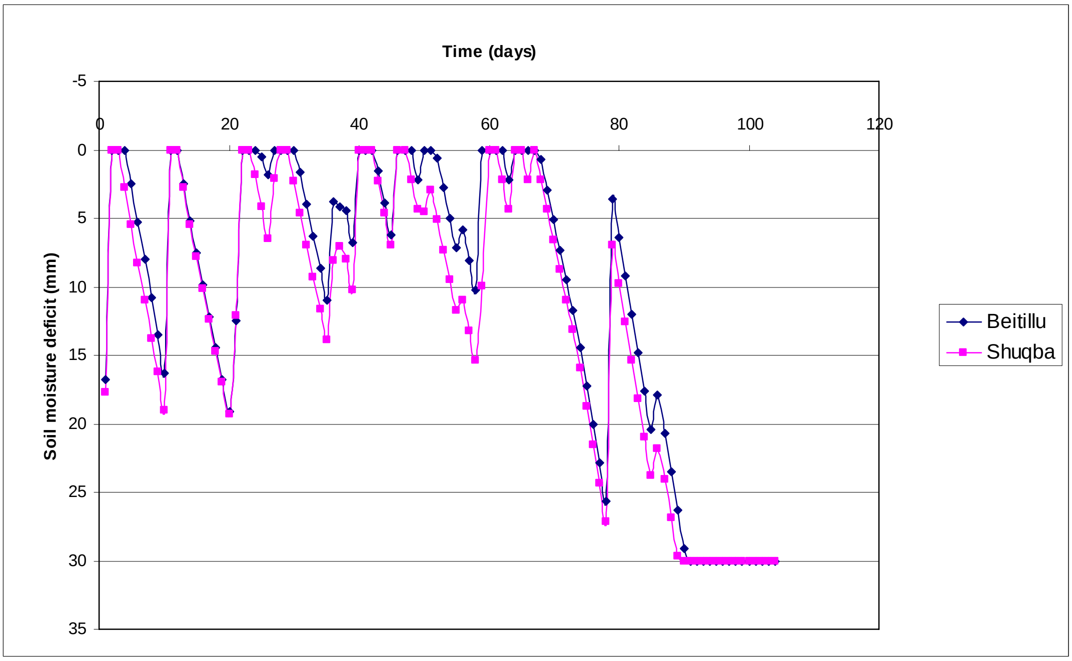


Figure 30 Numerical results of the soil moisture deficit at Beitillu and Shuqba using the wetting threshold recharge calculation method with WT = 30 mm

5 Application of the Recharge Model to the West Bank

5.1 INTRODUCTION

The recharge model has also been applied to estimate the recharge to the aquifers in the whole West Bank. The surface water movement and the resulting recharge in this modelling exercise are based on the application of either the SMD recharge method or the WT recharge method. Six numerical runs were undertaken to investigate the effect of changing the values of the parameters on the recharge values.

The recharge model can handle many of the flow processes describing the movement of the rainfall water. These processes are the surface flow processes and water percolation, the groundwater flow to shallow spring systems and the delay time required by the percolating water to leave the unsaturated zone and become part of the water table. The surface water movement from wadi floors is based on the local topographical and geological characteristics. In order to estimate the spring flow, however, a comprehensive understanding of the groundwater movement within the aquifers is required. In addition, the recharge model only represents shallow springs, i.e. springs discharging perched water. The springs in the West Bank are connected to the Lower and Upper Aquifers and so there is no need to include them in the model at this scale. No delay time for water to leave the unsaturated zone is considered in this exercise.

The results are presented for the three basins in the West Bank (Figure 31).

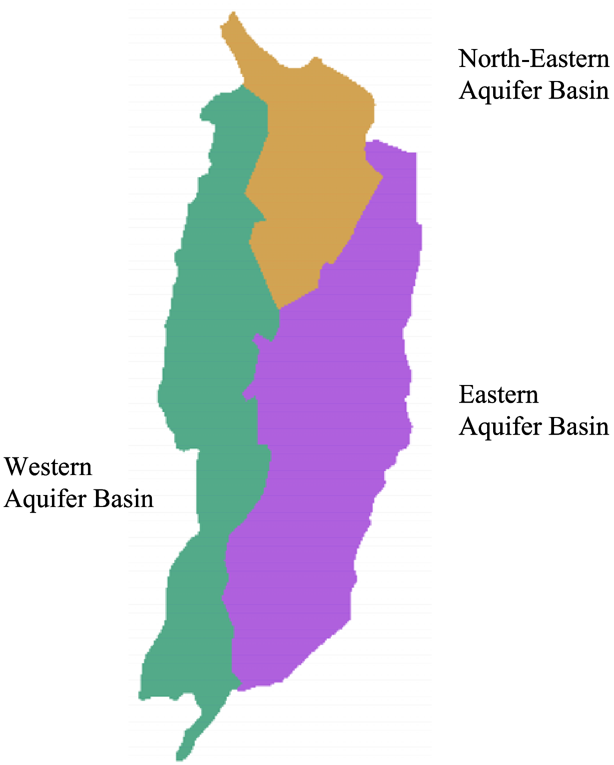


Figure 31 The West Bank aquifer basins

5.2 DATA REQUIREMENTS

5.2.1 Introduction

A 400 m square cells grid is used to represent the study area in the recharge model (Figure 32). The selection of the cell size is based on a compromise between the accuracy of the representation of the special features of the area such as the wadis, and the run time required by the model to produce the final results. The use of 1000 m square cells grid was too coarse as it resulted in merging separate streams together. The use of the 400 m square-cells grid, on the other hand, necessitated the construction of approximately 40000 nodes to represent the study area. Further grid refinement could increase the accuracy of the representation of these features but will greatly increase the number of nodes and could increase model run time markedly.

5.2.2 Rainfall

The daily rainfall data, prepared by Newcastle University, are based on a grid with 1000 m square cells. To overcome the inconsistencies between the sizes of the model grid cells and the rainfall grid cells, the recharge node points to the nearest lower left rainfall node to obtain the required rainfall data (see Appendix 3). More than one recharge node receives, in this case, the same rainfall amount. The rainfall data were provided for the years 1990 to 1997 and consist of one rainfall data file for each rainy day. These files are exported directly from GIS and are (.asc) files. At the beginning of each daily time step, the recharge model opens the corresponding rainfall file and extracts the required information from it. If the file does not exist, the model assumes that no rainfall has occurred during that specific time step and zero rainfall values are imported into the model.

5.2.3 Potential Evaporation

The recharge model needs the monthly potential evaporation data and the spatial distribution of the LTA values. The six available meteorological stations in the West Bank are used to produce the evaporation input data. These stations together with their monthly potential evaporation are listed in Table 9. To generate the spatial distribution of the potential evaporation, the evaporation values given in Table 9 are firstly averaged for each evaporation station. Secondly, the contour lines representing the areas with the same LTA evaporation are prepared, based on these average values and the location of the evaporation stations. Finally, the data are gridded in an appropriate format and included in the recharge model. The potential evaporation at each node was then determined by multiplying the PE value of the meteorological station the node belongs to by the ratio of the long-term average value calculated at this node to the long-term average value of the considered meteorological station. This approach ensures a smooth transition in the PE values from one PE zone to another.

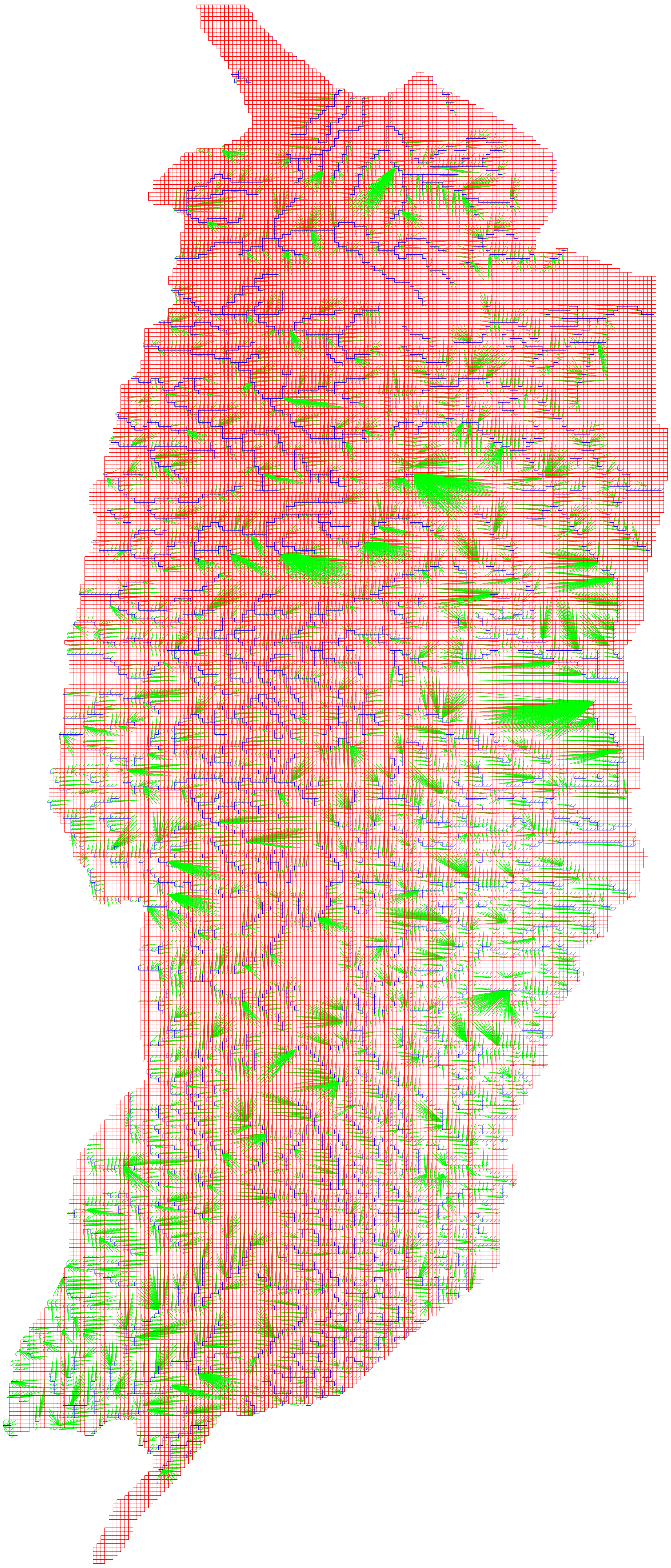


Figure 32 Model grid, wadis and runoff routing for the West Bank model

Table 9 Monthly PE for evaporation stations in the West Bank

	Monthly PE (mm month^{-1})					
	Hebron	**Jenin**	**Jericho**	**Maithalun**	**Nablus**	**Tulkaram**
Jan	68.1	69.0	65.1	42.4	68.2	77.5
Feb	64.4	78.2	75.4	45.0	72.5	87.0
Mar	82.2	110.4	114.7	65.6	99.2	93.0
Apr	149.1	170.7	184.8	127.9	171.0	150.0
May	176.8	244.6	251.1	188.9	226.3	155.0
Jun	232.5	270.4	285.0	222.2	246.0	150.0
Jul	280.0	300.8	297.6	240.6	266.6	186.0
Aug	217.0	257.7	260.4	222.2	217.0	198.4
Sep	175.9	207.7	213.0	168.0	177.0	180.0
Oct	123.4	93.6	145.7	145.8	142.6	155.0
Nov	138.2	111.8	93.0	142.0	102.0	180.0
Dec	80.8	68.9	62.0	43.5	65.1	155.0
Total	1788.4	1983.8	2047.8	1654.1	1853.5	1766.9

5.2.4 Landuse

The landuse type specified at a recharge node controls the values of the root constant (C) and the wilting point (D) at this node if the SMD recharge calculation type is applied, or the values of the wetting threshold (WT) if the WT recharge calculation type is applied. In the current study, two different sets of runs have been made. The first set is based on the SMD method where C and D values are set according to the landuse types detailed in Tables 10 and 11. The second set of runs is based on the application of the WT method where the WT values are considered to be constant everywhere in the study area.

Preliminary investigations suggest that the West Bank can be split into two sub-areas. The first, occupying the north-west part of the West Bank, is characterised by a sub-humid climate with the potential of significant recharge occuring during the wet season. This may lead to a development of a thick soil cover and more vegetation. The second sub-area occupies the south-east part of the West Bank, is more arid than the first sub-area and with a potential of a much less recharge. The less arid environment that characterises the first area may allow the application of the SMD recharge calculation type over it if the soil moisture reaches the field capacity, i.e. after a wet period. The recharge process taking place within the first sub-area may also follow the WT recharge calculation type. Therefore, the inclusion of both landuse types in a single run is not considered, instead separate runs, each with one landuse type, have been undertaken.

Table 10 C and D values of the SMD method based on landuse type (Lerner et al., 1990)

Landuse Description	Root constant (C) in mm	Wilting point (D) in mm
Arable Land	See Table 11	
Builtup	50	80
Dead Sea	1000	1000
Irrigated Farmland	See Table 11	
Israeli Settlement	50	80
Permanent Crops	See Table 11	
Rough Grazing	76	127
Woodland	203	254
Undefined	50	80

Table 11 Monthly variation of C and D values (Lerner et al., 1990)

	Root constant (C) in mm	Wilting point (D) in mm
Jan	31.25	41.25
Feb	38.75	52.5
Mar	48.75	65
Apr	74	108
May	86.5	131.75
Jun	82.75	128
Jul	79	126.75
Aug	61.75	88
Sep	51.75	70.5
Oct	51.75	65.5
Nov	48.3	33.75
Dec	30	33.75

5.2.5 Runoff Routing

A map of aspect directions has been prepared for the West Bank using the available digital terrain data. The aspect direction at a node controls the movement of the surface water, generated as a proportion of both the rainfall and the water received from an adjacent node, to one of its four adjacent nodes. The runoff coefficient value at a recharge node is set according to the geological characteristic this node represents. In the current study, with the exception of the Yatta and Senonian, a value of 0.3 is set, based on the experience with the Natuf study. A runoff coefficient value of 0.5 is set for nodes representing the Yatta, which is an aquitard and therefore produces more runoff than the other more permeable units. A value of 0.9 is set for nodes representing the Senonian, which are of low permeability. Similar to the routing process applied to the Natuf catchment, it is assumed that when water overpasses a node, a percentage of this water will be lost to this node. The overland loss coefficient which controls the amount of water lost is set to a constant value of 0.0005 m^{-1}.

Because of the large scale of the study area, a problem of automatically connecting all recharge nodes to the stream nodes is encountered. This problem is caused by the discretisation of the area which led to a loss in the accuracy of the DTM information and by converting the discretised topographical information to aspect direction data. It should be noted that the accuracy of stream delineation is also questionable. This has led to the formation of patches of areas with nodes that are not connected to stream nodes. The recharge model assumes that if the routed runoff water does not reach a stream node it goes to a virtual pond. The recharge from ponds, however, is much higher than the recharge caused by wadi losses and an error is introduced by simply leaving these areas without a stream connection. This has necessitated a manual modification of the aspect map to connect these areas to the nearest available streams. This operation may not be entirely complete and some virtual ponding may still exist.

5.2.6 Wadi Losses

As stated in the previous section, the accuracy of the delineation of streams is important for the connection of recharge nodes to the stream nodes. However, it is found that the unrealistic 400 m square cells stream nodes reduce the problem associated with stream delineations to one factor. This is the extent of streams i.e. the number of nodes that represents the stream. The detailed representation of stream shape perpendicular to the direction of the stream flow is of less importance. At the end of the daily time step, the flows collected at the stream nodes are cumulated in the downstream direction. Water losses are assumed to occur during this process through the wadi beds. 1% of the total daily flow calculated at a stream node is assumed to infiltrate directly to the unsaturated zone.

5.2.7 Urban Areas

Nine urban areas are identified in the West Bank area. The assessment of the water supplied to these areas and the magnitude of infiltration from the water mains and sewers are discussed in McKenzie et al. (2001). The values of water supply are extracted from this report and are detailed in Table 12. The losses from the water mains and sewers are assumed to be 30% and 20% respectively.

The urban recharge nodes include two recharge processes. The first represents the direct infiltration of water from water mains and sewers, and the second represents the recharge generated from rainfall that obeys the SMD recharge calculation method. The second recharge process reflects the presence of parks and green areas located within the urbanised areas. In the current study it is assumed that 20% of the urban area consists of green areas. The root constant C, the wilting point D and the empirical constant that specifies the amount of water lost when $C < SMD < D$ are set to values of 30 mm, 60 mm and 0.1 respectively. The runoff coefficients of the green areas and the impermeable areas are set to values of 0.4 and 0.9 respectively.

Table 12 Water supply for urban areas

Town	Water supply ($Mm^3 a^{-1}$)
Bethlehem	4.5
Jenin	2.7
Jericho	1.4
Jerusalem	8.1
Hebron	6.3
Nablus	6.9
Ramallah	6.9
Salfit	0.8
Tulkarem	4.4

Unlike the other recharge nodes, all nodes of each urban area are connected to one specified stream node, used to represent a wadi, regardless of the information given by the aspect direction map. This is to represent storm water sewers discharging at the specified stream node rather than routing the surface water to the nearest stream. In this study, a large urban area is split into sub-areas wherever a wadi goes through it or when its topographical characteristics shows the possibility of discharging the sewers to more than one location. Nablus, for example, is divided into two sub-areas, Ramallah, Bethlehem, and Hebron are divided each into three sub-areas and Jerusalem is divided into four sub-areas. These divisions together with the specified sewer discharging locations are based on the available topographical information and should be further verified on site.

5.2.8 Irrigated areas

The irrigated areas in the West Bank are grouped into five separate sets. It is assumed that irrigation water is applied uniformly across each area. The dry season is assumed to extend over seven months from April to October. The yearly irrigation water (Q_y) is distributed over these based on the distribution factors shown in Table 13. The root constant C, the wilting point D and the empirical factor that determines the amount of water lost from the ground when the SMD level falls between the C and D values are set to 0.3 mm, 0.6 mm and 0.1 respectively. Table 14 details the amount of applied water, the transmission losses and the field losses at each of these areas.

Table 13 Distribution of the yearly-applied irrigation over the dry season months

Month	April	May	June	July	August	September	October
Fraction of the yearly applied water (Q_p) (-)	0.067	0.133	0.2	0.2	0.2	0.133	0.067

Table 14 Irrigation areas in the West Bank

Name	Irrigation ($Mm^3 a^{-1}$)	Field losses	Transmission losses
North Jordan Valley	17.28	0.25	0.15
Nablus	14.65	0.25	0.15
Jericho	34.84	0.25	0.15
Tulkaram	16.62	0.25	0.15
Other	5.75	0.25	0.15

5.3 MODEL RESULTS

5.3.1 Simulation from January 1990 to December 1996

Various runs have been undertaken for the West Bank recharge model and are summarised as follows:

- Wetting threshold (WT) method with a WT of 20, 30 and 40 mm
- Soil Moiture Deficit (SMD) method using C and D values distributed on landuse
- Urban areas included for both methods; for a WT of 30 mm and SMD
- Irrigated area included for both methods; for a WT of 30 mm and SMD

A full set of LTA output from these runs can be found in Appendix 4.

The interpretation of the long term average results produced by the recharge model shows that the use of the WT recharge calculation method, with WT values of 20, 30, or 40 mm yields more recharge than the SMD recharge method (Table 15). The increase of the amount of recharge caused by reducing the WT value from 40 mm to 20 mm is in the order of 17% while the difference in the result produced by using WT of 20 mm and the one produced by the SMD method is approximately 64%. The reason behind the relatively large difference in the LTA recharge values between the WT and SMD method is due to the larger soil store that needs to be satisfied before recharge will occur (see Tables 10 and 11 for C and D values).

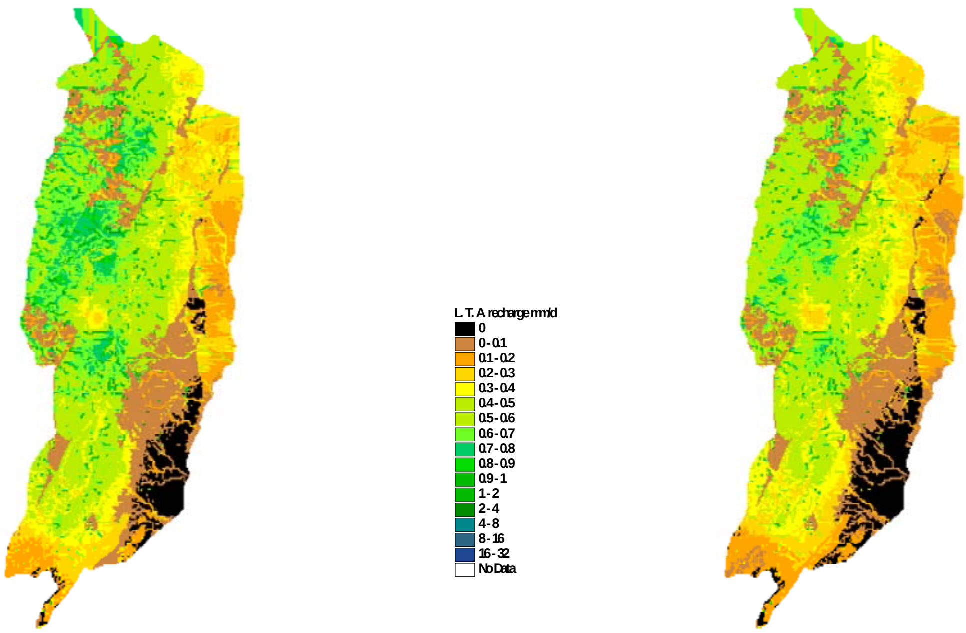
Table 15 Total long-term average recharge values

	WT 20 mm	WT 30 mm	WT 40 mm	SMD	WT 30 mm/ Urban	SMD/ Urban	WT 30 Urban Irrig.	SMD Urban Irrig.
Total $Mm^3 d^{-1}$	2.74	2.50	2.33	1.67	2.55	1.75	2.65	1.85
Total mm a^{-1} (Area ~ 6450 km^2)	155	141	132	95	144	99	150	105

Figure 33 shows the spatial distribution of the calculated LTA recharge using the wetting threshold method with WT values of 20mm and 40mm respectively. The same pattern of recharge distribution can be identified in both of these figures. The Western Aquifer Basin, for example, receives the maximum amount of recharge and the south-east of the West Bank receives only a small amount of recharge and includes a large area that receives little or no recharge. The zero recharge zone increases when the WT is set to 40 mm. The contrast of having zero recharge in an area characterised by the existence of a large number of wadis can be explained by the fact that whatever the significance of the rainfall, the formations constituting this area are preventing recharge and transforming all rainfall to runoff.

The effects of including wadi losses and the spatial variation of the runoff coefficient values are also clearly reflected in the spatial distribution of LTA results e.g. Figure 31. Linear features, showing higher recharge than the surrounding areas, represent streams where the wadi flows are generated by runoff and infiltrate to the unsaturated zone through the stream floors. The areas showing less recharge than expected in the western part of the West Bank, reflects the assignment of high runoff coefficient values to these areas. A closer investigation reveals that these areas are coincident with outcrops of the Yatta and the Senonian and where the runoff coefficient values are increased to 0.5 and 0.9 respectively.

Figure 34 shows the spatial distribution of recharge resulting from the application of the SMD method. Although this figure shows the same general pattern as the WT method it is found that recharge exhibits much more spatial variation. The reason behind this is that SMD method includes more factors that control the amount of resulting recharge than the WT method. The WT method offers a clearer reflection to the rainfall and evaporation distribution in the area than the SMD method. This is due to the spatial variation in landuse and, therefore, the C and D values in the SMD method, whilst the WT values in the wetting threshold method are set to the one value everywhere. However, for the SMD method, the reduction of recharge caused by the increase of the runoff coefficient and the increase of recharge caused by the wadi losses are still identifiable.



(a) (b)

Figure 33 Spatial distribution of recharge resulting from the application of the wetting threshold method. (a): WT = 20 mm. (b): WT = 40 mm.

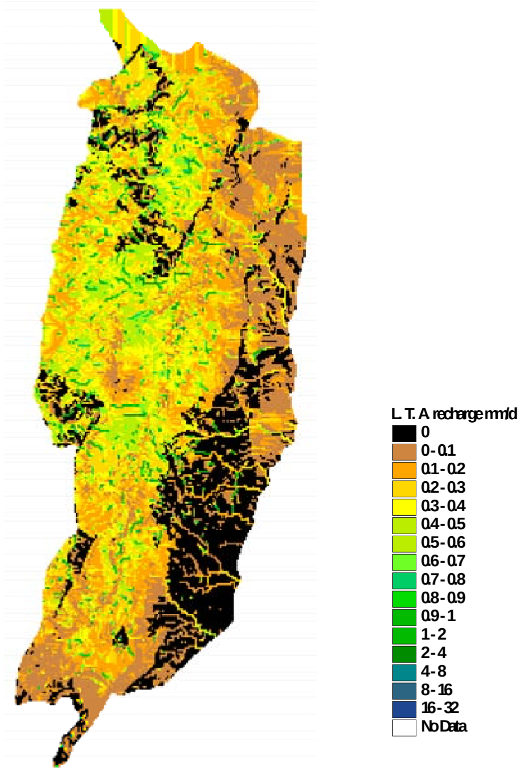


Figure 34 Spatial distribution of recharge resulting from the application of the SMD method

Table 16 gives the LTA recharge values calculated at each of the three basins constituting the West Bank area and using the WT method with the wetting threshold equal to 20, 30 and 40 mm and using the SMD method. Table 16 shows that the Western, North-Eastern and Eastern Aquifer basins receive 45%, 22% and 32% of the total calculated recharge respectively. However the maximum recharge per area is at its maximum at the North-Eastern basin. This 0.15 mm a^{-1}/km^2 at this basin compared to 0.09 mm a^{-1}/km^2 and 0.037 mm a^{-1}/km^2 at the Western and Eastern Aquifer Basins respectively when using the WT method with WT = 20 mm. It should be noted that the sum of recharge of the three areas, shown in Table 16, totals to the recharge value given by Table 15. The three basins are illustrated in Figure 31.

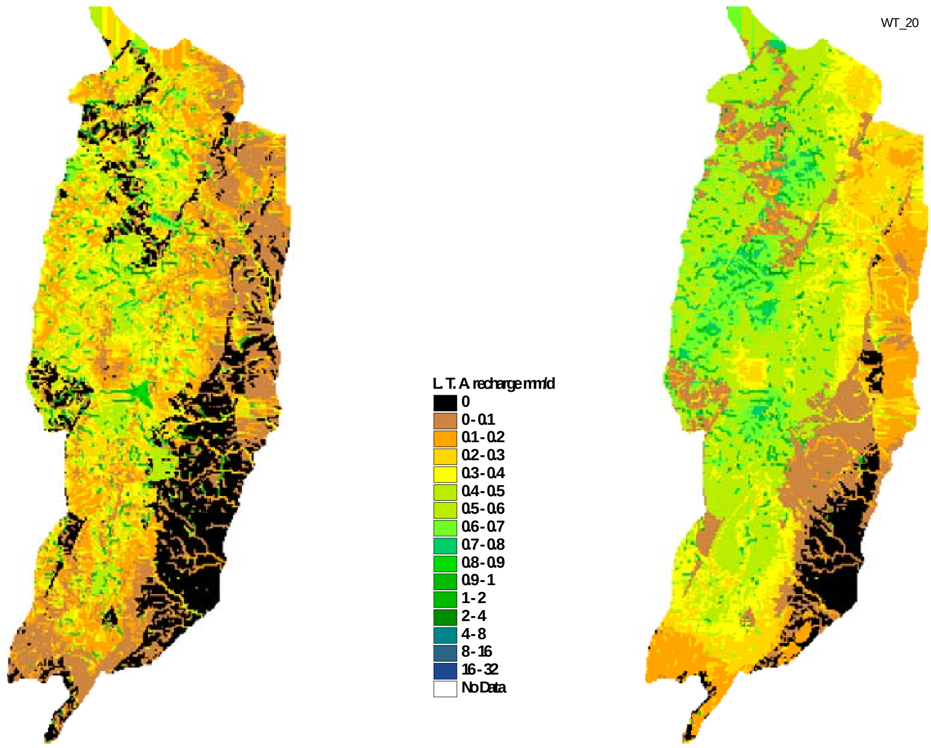
Table 16 Recharge values per basin

		WT 20 mm	WT 30 mm	WT 40 mm	SMD	WT 30 mm Urban + Irri.	SMD Urban + Irri.
Total inflow (Mm^3 d^{-1})	Western Aquifer Basin	1.25	1.14	1.06	0.74	1.18	0.79
	North-Eastern Aquifer Basin	0.62	0.57	0.54	0.40	0.59	0.42
	Eastern Aquifer Basin	0.88	0.79	0.73	0.54	0.88	0.65
Long-term average recharge (mm a^{-1})	Western Aquifer Basin (Area ~ 2273.6 km^2)	200.17	182.35	170.39	118.15	189.29	126.16
	North-Eastern Aqufier Basin (Area ~ 1229.28 km^2)	184.32	169.57	159.73	119.73	174.20	125.10
	Eastern Aquifer Basin (Area ~ 2949.44 km^2)	108.51	97.82	90.53	66.23	109.30	80.01

The inclusion of the urban areas increases the total amount of recharge by approximately 0.05 Mm^3 d^{-1} when the WT method is used and by approximately 0.07 Mm^3 d^{-1} when the SMD method is used. Setting the sewer loss factor to 20% and the water mains loss factor to 30% and having a total water supply of 42.9 Mm^3 a^{-1}, the average annual recharge caused by leakage from both sewers and mains can be directly determined and is equal to 21.45 Mm^3 a^{-1} which is equivalent to approximately 0.059 Mm^3 d^{-1}. The validity of the increase in the recharge values, however, is not straightforward because of changing the nodes representing the urban areas from ordinary recharge node type to urban area node type. In the latter type, the runoff coefficient is increased and the SMD recharge process that obeys the ordinary recharge mechanisms applies to a small part of the total urban area only.

Figure 35 shows the spatial distribution of recharge produced by runs considering the SMD calculation method and the WT calculation method with a WT of 30 mm respectively. The location of urban areas can be easily identified by comparing the results of these figures to those in Figures 33 and 34.

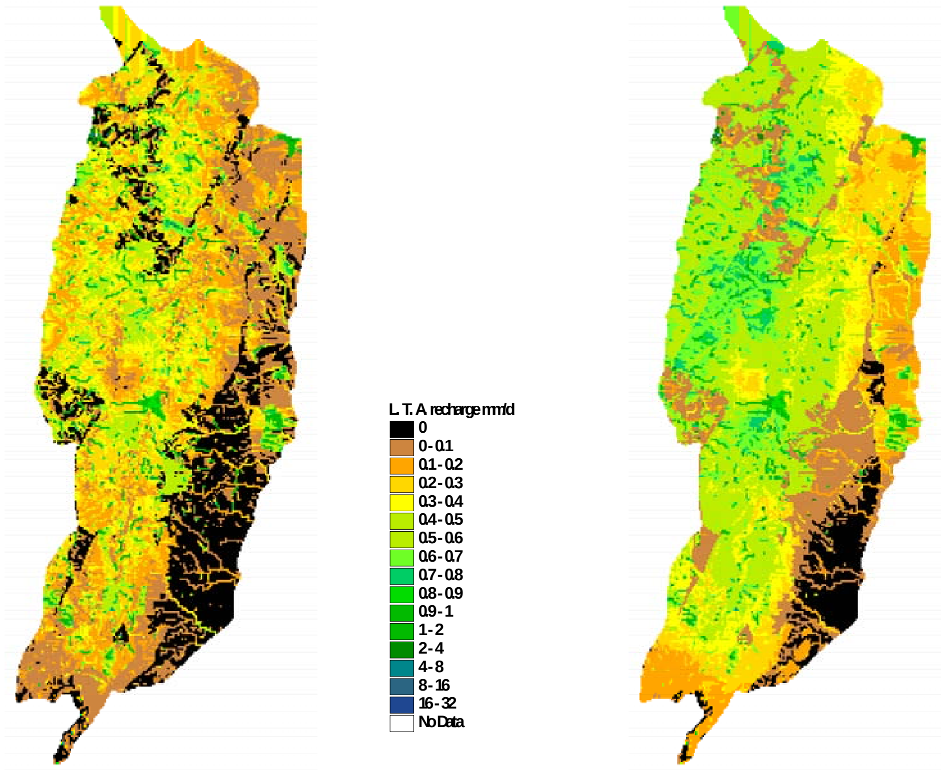
Figure 35 shows areas with more recharge potential resulting from continuous water leakage from urban area pipes to the unsaturated zone.



(a) (b)

Figure 35 Spatial distribution of recharge with the inclusion of urban areas. (a): SMD. (b): WT = 30 mm

Two additional runs have been performed to investigate the influence the irrigated areas may impose on the recharge results. The first run considers the application of the WT recharge process with WT equal to 30 mm and the second run considers the application of the SMD recharge process over the whole area. An additional recharge of 0.097 $Mm^3\ d^{-1}$ when the WT method is used and 0.109 $Mm^3\ d^{-1}$ when the SMD method is used has resulted from the inclusion of the irrigated areas which are equivalent to 35.4 $Mm^3\ a^{-1}$ and 39.8 $Mm^3\ a^{-1}$ respectively. These are almost half the total quantity of the yearly-applied irrigation water. Figure 36 show the spatial distribution of recharge over the West Bank for WT and SMD methods respectively when irrigated areas are included.



(a) (b)

Figure 36 LTA results with irrigation added. (a): SMD. (b): WT=30 mm

Careful examination of the LTA recharge results show a line running south-west to the north-east in the western basin with very different recharge values either side of it. This line is coincident with the boundary between the two Theissen polygons used for the potential evaporation calculation. Further examination of the monthly evaporation values at the meterological stations within these Theissen polygons shows that the ratio of the monthly PE values at Jenin to the monthly PE values at Tulkaram switches from being less than one during the winter to become greater than one during the summer. This change of ratios leads to problems with the calculation of a continuous distribution of PE and differences in the recharge at the boundary of the PE Theissen polygons. Correcting the monthly PE to keep the ratios of monthly PE consistent with the annual LTA PE removes this line as demonstrated by Figure 37.

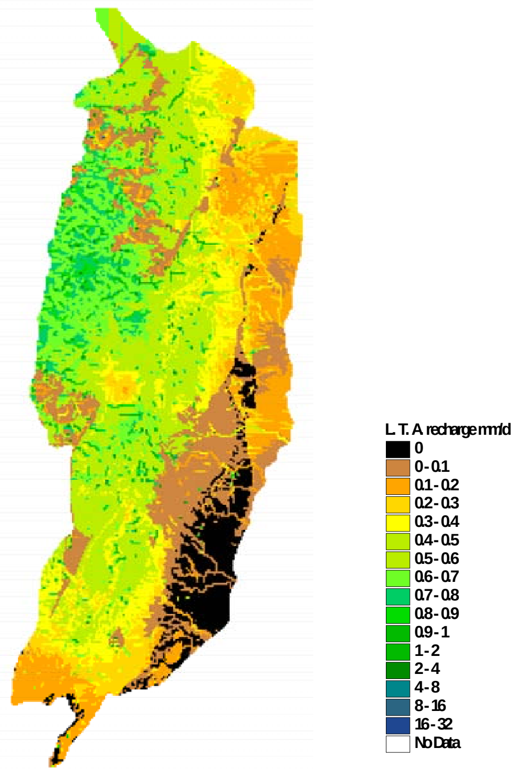


Figure 37   Spatial distribution of recharge resulting from correction of monthly PE values

The recharge model has the capability to produce the total daily flow at any gauging station for of any wadi. However, field stream flow measurements are required to validate the results. A total of 93 independent streams are identified in the West Bank area when a 400 m square cell mesh is used. The daily flow is monitored at the discharge node of all these streams.

To aid the validation of the West Bank recharge model, the wadi flows calculated by the model are compared with field measurements. Four wadi gauging stations were identified with which to compare model results (Table 17). These wadi gauging stations are as close as possible to the western boundary of the outcrop of the Western Aquifer Basin. Flow data was obtained from the Hydrological Service of Israel (HSI) yearbooks for the duration of the model simulation (January 1990 to December 1996) (Table 17). Data are limited, but nonetheless provide a useful method of validating the recharge model and runoff processes.

Table 17   Measured flows at wadi gauging stations

	Flow ($Mm^3\ a^{-1}$)			
	Qana	**Shillo**	**Natuf**	**Soreq**
HSI I.d.	177110	17125	17155	18107
Easting	146470	146420	141250	164800
Northing	172680	164020	154620	131900
1990-1991	0.204	0.014	0.539	0.12
1991-1992		34.2	70.3	12.7
1992-1993	6.44	14.3	10.1	3.41
1993-1994				0.396
1994-1995				
1995-1996	0.848		0.417	1.5
1996-				

Modelled wadi flows from the Wetting Threshold (WT = 30 mm) and the SMD runs are presented in Table 18 and Table 19. Generally, the modelled results show reasonable agreement with the measured flows. The best simulated year is 1992/3 where both the WT and the SMD method reproduce both the magnitude and pattern of measured flows. The poorest match is for 1990/1 where the modelled results overestimate the measured flows. This overestimate indicates that the method by which runoff processes are linked to rainfall intensity could be improved. Lower rainfall could mean a smaller proportion of rainfall runs off to wadis.

Table 18 Modelled flows for WT method (WT = 30 mm)

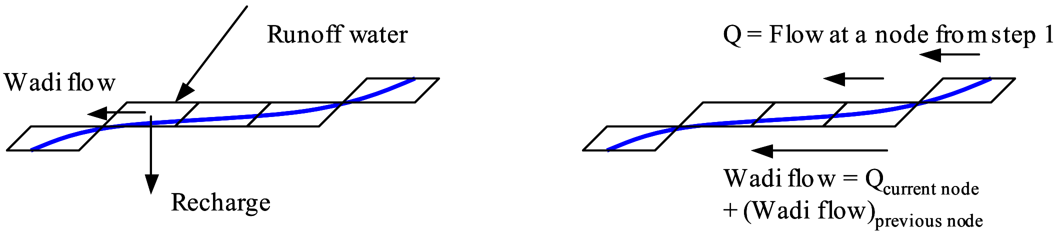
	Flow ($Mm^3 a^{-1}$)			
Year	**Qana**	**Shillo**	**Natuf**	**Soreq**
1990-1991	4.04	5.47	2.96	1.50
1991-1992	17.84	25.99	16.52	6.85
1992-1993	8.38	12.56	7.84	3.29
1993-1994	3.42	4.69	2.37	1.30
1994-1995	7.95	11.69	8.04	3.22
1995-1996	3.13	4.02	1.98	0.99
1996-	0.46	0.73	0.38	0.15

Table 19 Modelled flows for SMD method

	Flow ($Mm^3 a^{-1}$)			
Year	**Qana**	**Shillo**	**Natuf**	**Soreq**
1990-1991	9.67	14.29	8.60	3.53
1991-1992	22.48	34.10	21.32	8.49
1992-1993	13.39	20.18	12.57	4.89
1993-1994	8.80	13.11	7.94	3.24
1994-1995	14.09	21.09	13.74	5.22
1995-1996	9.57	14.04	8.62	3.41
1996-	2.73	4.08	2.54	0.89

5.3.2 Runs using long-term rainfall data sets (1961-2001)

The model, originally developed for this work, considers that at a certain stream node only a proportion of the runoff water is lost as recharge by the wadi loss mechanism (Figure 38). The remainder of the runoff water is added to the water transferred from the adjacent upstream node to form the total stream flow at this node (Figure 38). The model results listed in Table 16 are calculated based on this assumption. Recent development of the recharge model incorporates a different approach for calculating the wadi flows. This approach considers the wadi losses from a stream node as a proportion from the total stream flow calculated at a given node, i.e. the sum of the runoff water and the water transferred from the upstream node (Figure 39). This yields an increase in the total calculated recharge values (Table 20). When the wetting threshold method is applied everywhere in the study area, with a WT value of 30mm and including the irrigation and urban recharge, the long term average recharge increases from 2.65 $Mm^3 d^{-1}$ (Table 16) to 2.93 $Mm^3 d^{-1}$ for the West Bank. When the SMD type recharge calculation method is applied the long term average recharge increases from 1.85 $Mm^3 d^{-1}$ (Table 16) to 2.35 $Mm^3 d^{-1}$. Since the last wadi loss calculation approach is more representative it is followed in the subsequent calculations. The recharge values discussed in the next sections must therefore compare to the new LTA recharge values listed in Table 20 and not the old LTA recharge values listed in Tables 14.



(a) Step1 calculation of recharge

(b) Step 2 Calculation of wadi flows

Figure 38 Initial calculation method for wadi recharge

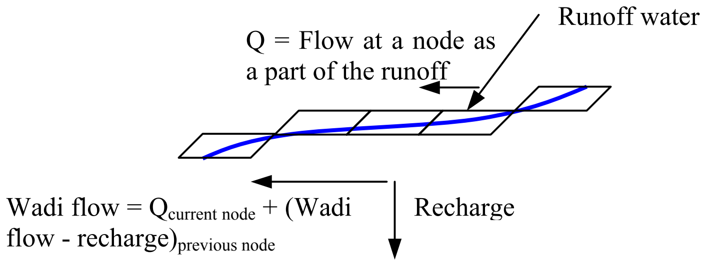


Figure 39 Updated calculation method for wadi recharge

Table 20 Comparison between the long term average results calculated using the old and the updated model codes (Area ~ 6450 km^2).

	LTA recharge results from old model code		**LTA recharge results from updated model code**	
	WT 30mm	SMD	WT 30mm	SMD
Total $Mm^3 d^{-1}$	2.65	1.85	2.93	2.35
Total mm a^{-1}	150	105	166	133
Total $Mm^3 a^{-1}$	967	677	1070	858

CALCULATION OF RECHARGE USING A MIXED WT AND SMD CALCULATION METHODS

The recharge results presented in the previous section show that 45 % of the calculated recharge occurs at the Western Aquifer Basin while the maximum recharge occurs at the North-Eastern Aquifer Basin. This clearly indicates that the Western and the North- Eastern basins are much wetter than the Eastern Basin. Additionally, it can be seen that recharge reduces southwards. This recharge pattern reflects, to some extent, the rainfall distribution over the West Bank. The greater availability of rainfall, and consequently the development of the top soil which allows agricultural activities to take place, increases the potential recharge. The SMD calculation method is, therefore, most likely to be applicable in these areas while the WT calculation method is most likely to be suitable for recharge calculation in the drier south and east areas of the West Bank. The plot of the long-term average rainfall distribution over the West Bank () and the plots of the long-term average recharge (Figure 33 etc) show that recharge intensity of 0.3 mm day (110 mm a^{-1}) is found where rainfall is greater than 500 mm a^{-1}. This 500 mm a^{-1} rainfall contour is taken as the divider between the areas where the WT and SMD calculation methods are applicable (Lerner et al., 1990). This contour line divides the West Bank into two zones, the north-west zone where the SMD method is applied and the south-east zone where the WT method is applied (Figure 41). All the simulations described next consider the combination of the SMD and WT calculation methods to calculate the recharge of the West Bank.

Table 20 shows that the application of the wetting threshold method over the whole study area yields a LTA recharge value of 166.0 mm d^{-1} while the application of the SMD method yields a recharge value of 133.0 mm d^{-1}. When the combination of these two methods is considered, the LTA recharge value is estimated to be of 143.5 mm d^{-1}.

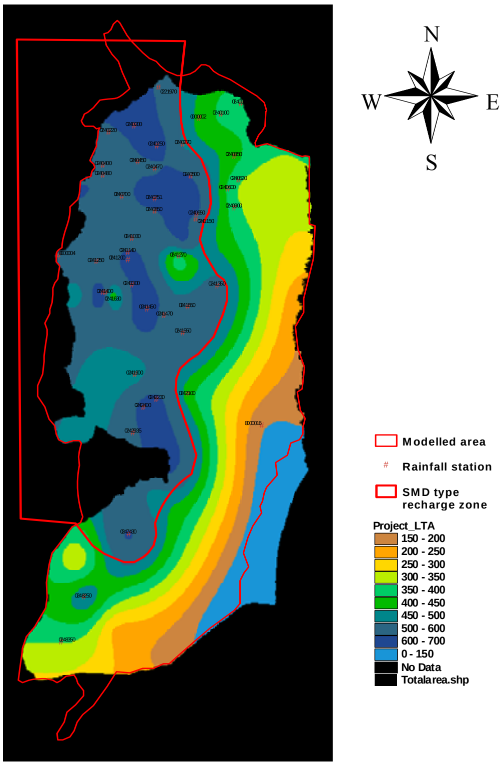


Figure 40 Long term average distribution of rainfall

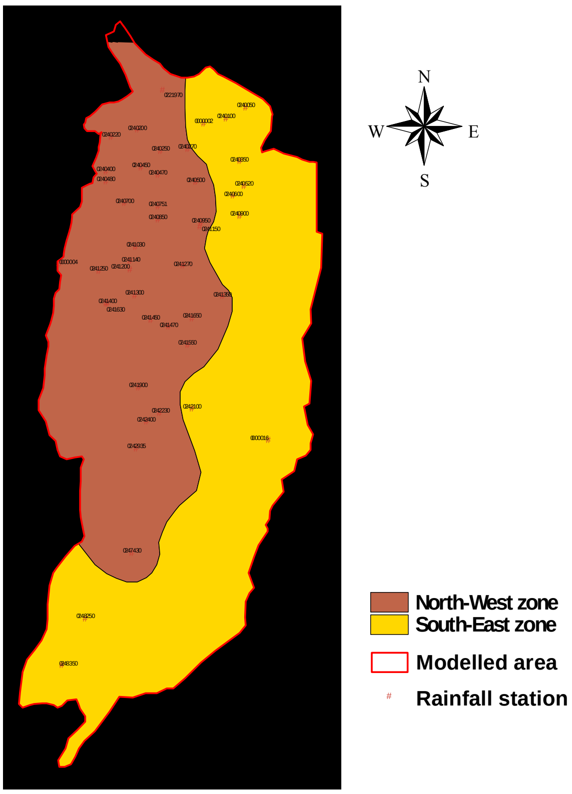


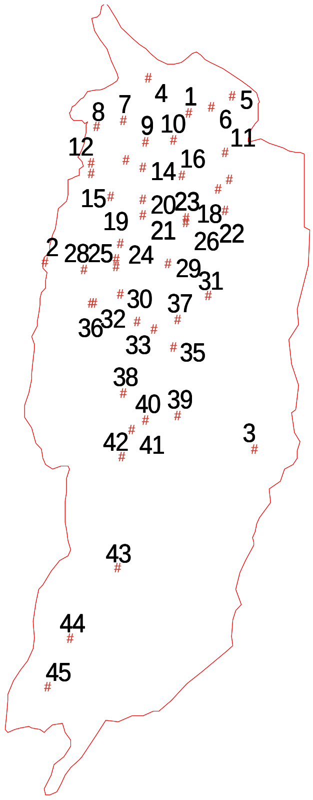
Figure 41 Zones where the WT and SMD recharge calculation methods area applied

DISCUSSION OF RESULTS

The winters of the years from 1990 to 1997 are characterised by being relatively wet which may lead to the overestimation of recharge. In this section, the Long Term Average (LTA) recharge is calculated based on the available historical records that start from 1961. The historical data are available from Newcastle University in the form of gridded ASCII files. The LTA recharge is also calculated from rainfall data recorded at the rainfall stations using existing routines within the recharge model. While rainfall stations give rainfall values at single points, distributed rainfall values over the modelled area are needed. These are determined as follows. First the LTA rainfall values are calculated at the rainfall stations and a distribution of rainfall expressed as contours are constructed based on these values. These contour lines are then gridded and converted into an ASCII file that can be accessed by the numerical model. Finally Theissen polygons that relate each node to one rainfall station are built. Figure 42 shows the distribution of the rainfall stations in the West Bank area.

While the rainfall records at the rainfall stations are available from the year 1967 onwards, the historical rainfall data provided by the Newcastle University starts from 1961. The simulation that considers rainfall data, is undertaken from 1967 to 1997 and results in a long-term average recharge value of 106.2 mm a^{-1}. The simulation that uses the Newcastle University data, from 1961 to 1991 produces a long-term average recharge of 135.2 mm a^{-1}, which is higher than the value produced when data at rainfall stations are used. As expected these two simulations produce LTA recharge values that are smaller than the recharge value produced by the simulation starting in 1990 and ending in 1997. However, the production of a LTA recharge value from the historical simulation from 1961 to 1991 that is higher than the LTA recharge value from the simulation from 1967 to 1997 is suspect since the latter simulation includes the wet winter of 1992/3.

An additional run is, therefore, undertaken using the data at the rainfall stations but for the period of 1990 to 1997 to compare the results produced when the Newcastle University data are used to the results produced when data at rainfall stations are used but using the same period of time. This simulation produces a LTA recharge value of 120.4 mm a^{-1} which is smaller than the 143.5 mm a^{-1} produced when the Newcastle data are used. This reveals the tendency of the Newcastle data to produce high recharge values. It should be noted, however, that data from rainfall stations include errors and missing records that have to be corrected or accounted. This leads to discrepancy in the produced results but the magnitude of this discrepancy is hard to evaluate. The long-term average recharge values of the four simulations are listed in Table 21.



Rainfall station Number	Rainfall station id	Rainfall station Number	Rainfall station id
1	0000002	24	0241030
2	0000004	25	0241140
3	0000016	26	0241150
4	0221970	27	0241200
5	0240050	28	0241250
6	0240100	29	0241270
7	0240200	30	0241300
8	0240220	31	0241350
9	0240250	32	0241400
10	0240270	33	0241450
11	0240350	34	0241470
12	0240400	35	0241550
13	0240450	36	0241630
14	0240470	37	0241650
15	0240480	38	0241900
16	0240500	39	0242100
17	0240520	40	0242230
18	0240600	41	0242400
19	0240700	42	0242935
20	0240751	43	0247430
21	0240850	44	0248250
22	0240900	45	0248350
23	0240950		

Figure 42 The distribution of rainfall stations in the West Bank area

Table 21 Historical LTA recharge values

		1990 to 1997 Rain gauge	1967 to 1997 Rain gauge	1990 to 1997 Newcastle data	1961 to 1991 Newcastle data
Recharge per basin ($Mm^3\ d^{-1}$)	Western Aquifer Basin (Area ~ 2273.6 km^2)	0.80	0.75	1.06	0.99
	North-Eastern Aquifer Basin (Area ~ 1229.28 km^2)	0.56	0.46	0.53	0.50
	Eastern Aquifer Basin (Area ~ 2949.44 km^2)	0.77	0.67	0.94	0.89
Total recharge ($Mm^3\ d^{-1}$)	(Area ~ 6450 km^2)	2.13	1.88	2.53	2.38
Recharge per basin ($mm\ a^{-1}$)	Western Aquifer Basin	128.6	119.8	170.7	159.6
	North-Eastern Aquifer Basi	165.5	136.7	157.1	149.2
	Eastern Aquifer Basin	95.2	83.0	116.7	110.5
Total Recharge ($mm\ a^{-1}$)		120.4	106.2	143.5	135.2

5.3.3 Estimated recharge values using climate change scenarios

RAINFALL DATA USED

The LTA recharge values are also estimated using predicted rainfall data for the years 2001-2026 provided by Newcastle University (Kilsby et al., 2005). Two sets of rainfall data for this period are prepared, Set A2 and Set B2, with each set describing a different pattern of rainfall. The rainfall series were created using the Hadley Centre rainfall time series (HadRM3) for two different climate change scenarios; high emissions scenario (A2) and medium emissions scenario (B2) using rainfall data collected from raingauges in the West Bank. A third scenario (CON), used for control, was created for 1961 – 1990.

SIMULATIONS UNDERTAKEN

Two prediction simulations are undertaken and the calculated LTA recharge values are compared to the LTA recharge values of the historical 1961-1991 simulation. The predicted LTA recharge values of these two simulations are 109.9 mm a^{-1} and 127.1 mm a^{-1} using rainfall Set A2 and Set B2 respectively. These values are lower than the historical LTA recharge value (135.2 mm a^{-1}) as shown in Table 22. The high emission scenario (A2) leads to the lowest recharge. The results from the medium emission scenario (B2) are slightly lower than the control (CON) results. These results suggest that recharge will be similar to the current values unless the high emission scenario occurs.

Table 22 LTA recharge values using predicted rainfall data for the years 2001-2026

		1961 to 1990 Newcastle data CON	2001 to 2026 Newcastle A2	2001 to 2026 Newcastle B2
Recharge per basin ($Mm^3 d^{-1}$)	Western Aquifer Basin (Area ~ 2273.6 km^2)	0.99	0.81	0.94
	North-Eastern Aquifer Basin (Area ~ 1229.28 km^2)	0.50	0.41	0.47
	Eastern Aquifer Basin (Area ~ 2949.44 km^2)	0.89	0.73	0.84
Total recharge ($Mm^3 d^{-1}$)	(Area ~ 6450 km^2)	2.38	1.95	2.25
Recharge per basin ($mm a^{-1}$)	Western Aquifer Basin	159.6	129.5	150.1
	North-Eastern Aquifer Basin	149.2	120.8	140.2
	Eastern Aquifer Basin	110.5	90.2	103.8
Total Recharge ($mm a^{-1}$)		135.2	109.9	127.1

6 Summary and Conclusions

6.1 APPLICATION OF RECHARGE MODEL AND DISCUSSION OF RESULTS

The distributed object-oriented recharge model has been applied to both the Wadi Natuf catchment as a pilot study, and the outcrops of aquifers in the West Bank. Based on the recharge mechanisms identified in the West Bank, the models were set up with the best available data sets. Where field data exist, modelled output was compared with observed values and areas where the recharge model could be improved were identified.

6.1.1 Wadi Natuf recharge model

The Wadi Natuf recharge model covers the surface catchment of the Wadi Natuf. The total area of the model is 107.2 km^2 and it extends from easting 150.4 to 168.9 and from northing 149.0 to 158.3. The model grid used for the recharge calculation is 200 m by 200 m. The wetting threshold method was applied for the whole of the Wadi Natuf catchment with a value of WT of 30 mm. Rainfall data were provided on a 1 km^2 mesh by Newcastle University. The potential evaporation data are from the Hebron meterological station and have been factored for spatial distribution. Landuse data are used to characterise the distribution of runoff coefficients. For example, the runoff coefficient is decreased to 40% in olive growing areas. Six spring groups are identified for inclusion in the model, these are located in Wadi Zarqa, Beitillu, Jammala, Ras Karkar, Kobar and Anu Skhedem. The model simulation was undertaken from January 1990 to December 1996. This simulation period was determined by the length of rainfall record supplied by Newcastle University.

Model output is produced for potential recharge to the unsaturated zone, springflow for six spring groups and wadi flows at selected points along the wadis. The long-term average recharge for the Wadi Natuf catchment is calculated at between 152 and 206 mm a^{-1}, depending on the wadi leakage chosen. The lower value of recharge (152 mm a^{-1}) corresponds to no wadi losses. This value of recharge compares favourably with the estimate of recharge for the catchment by the SUSMAQ team (136 mm a^{-1}; Abu Sa'ada et al., 2004) as this value does not include wadi losses.

Springflows are produced on a daily basis, but currently no data exist with which to validate them. The springflow in the recharge model is controlled by two factors; a time of travel and the proportion of recharge routed to the springs from the soil zone. Sensitivity was undertaken on the springflows to determine the effect of changing the time of travel parameter. Setting a value of time of travel of 20 m d^{-1} produced "flashy" springs, whereas using a value of 5 m d^{-1} produced more continuous flows (i.e. baseflow springs). Once data are collected for the Wadi Natuf study and the behaviour of the springs clarified, the time of travel parameters can be set with more confidence.

Examining the flow records from the HSI yearbook show that the Wadi Natuf at the Natuf 'C' gauge flows for between 5 and 10 days each year. Comparing the modelled wadi flows with field data demonstrates that the frequency of flows is reproduced. The absolute values of flow are not matched very well, however, and more work needs to be undertaken on refining the runoff mechanism.

6.1.2 West Bank recharge model

The West Bank recharge model covers the geographical extent of the West Bank and includes the relevant aquifer outcrops, which extend outside of the West Bank. The total area of the model is 6450 km^2 and it extends from easting 137.3 to 205.4 and from northing 69.3 to

229.6. The model grid used for the recharge calculation is 400 m by 400 m. Rainfall data was provided on a 1 km^2 mesh from Newcastle University. The potential evaporation data used are mean monthly data from six meterological stations and factored for spatial distribution. For the SMD method, landuse data informs the choice of C and D coefficients for the soil moisture balance method. The mechanisms that are included in the model are runoff routing to wadis and subsequent infiltration, urban recharge processes and enhanced recharge due to losses from irrigation schemes. Similarly for the Wadi Natuf recharge model, the model simulation was undertaken from January 1990 to December 1996. Again, this simulation period was determined by the length of rainfall record supplied by Newcastle University.

In all, a series of nine simulations of the recharge model were undertaken. Three runs were undertaken to examine the impact of varying the wetting threshold; WT = 20, 30 and 40 mm, together with a single SMD run. For the basecase wetting threshold (WT = 30 mm) and the SMD run, two further sets of runs were undertaken with urban recharge processes and losses from irrigated fields activated. Finally one run was undertaken to examine the impacts of smoothing the PE data.

The output from the West Bank recharge model was summarised in three ways; total and basinal recharge estimates for the Western, Eastern and North-Eastern Aquifer Basins, spatial distribution of long-term average recharge and annual summaries of surface water flows. The results were then examined to determine whether the recharge model was producing justifiable estimates of recharge.

The long-term average recharge calculated for the western aquifer basin period January 1990 to December 1996 by the recharge model varies between 0.74 $Mm^3 d^{-1}$ (269 $Mm^3 a^{-1}$) for the SMD approach and 1.25 $Mm^3 d^{-1}$ (455 $Mm^3 a^{-1}$) for the wetting threshold method, with WT=20 mm. The most likely long-term average recharge value is between these two extremes, for example wetting threshold value of 30 mm with urban recharge processes and irrigation losses results in recharge of 1.18 $Mm^3 d^{-1}$ (430 $Mm^3 a^{-1}$) to the Western Aquifer Basin. These estimates compares well with the previous values of long-term average recharge calculated for the Western Aquifer Basin of between 317.5 and 360 $Mm^3 a^{-1}$.

Studying the maps of long-term average recharge shows a common pattern for the results of each simulation. The highest recharge occurs in the north-west of the West Bank and the lowest in the south-east. This corresponds to the spatial distribution of recharge predicted from the balance between rainfall and potential evaporation. Other features which influence the distribution of recharge include the wadis which result in lines of enhanced recharge following the wadi beds, urban areas and, irrigated areas which results in "patches" of higher recharge.

Comparison of the model output with measured surface water flows has been undertaken to provide a further validation of the recharge model. Annual totals of wadi flows for each of the years the model has been run have been compared with measured flows. This has been undertaken for four wadi gauging stations whose flows are reported in the HSI yearbooks. These wadi gauging stations have been chosen to be as close as possible to the boundary of the outcrops of the western aquifer basin.

Generally, the modelled results show reasonable agreement with the measured flows. The best simulated year is 1992/3 where both the WT and the SMD method reproduce both the magnitude and pattern of measured flows. The poorest match is for 1990/1 where the modelled results overestimate the measured flows. This overestimate could indicate that the method by which runoff processes are linked to rainfall intensity could be improved. For example with a lower rainfall intensity, runoff will be a smaller proportion of rainfall. The runoff coefficient in the recharge model will, therefore, vary with rainfall intensity.

6.2 RECOMMENDATIONS FOR FURTHER WORK

The work described in this report has advanced the knowledge and quantification of recharge processes in the West Bank. However, this work is a step forwards in arriving at a full understanding of recharge to the main aquifer outcrops. Further work, therefore, is required to gain a comprehensive and detailed understanding of recharge processes operating in the West Bank.

- Improvements to conceptual understanding
    - Increase number of experimental catchments (i.e. Wadi Natuf), especially in the south of the West Bank
    - Undertake studies on wadi flows, how they are related to rainfall intensity
    - Undertake infiltration experiments similar to that reported in Lange et al (2003)
    - Determine impact of soil “pockets” on recharge in rocky areas
    - Investigate the role of karstification in recharge processes
    - Determine impact of the unsaturated zone on the timing and lateral movement of recharge form the soil zone to the water table
- Data requirements
    - Extend record of rainfall and run recharge model
    - Obtain a time series of PE data
    - Collate landuse data at a finer scale
    - Collect wadi discharges on a daily basis
    - Improve landuse mapping and knowledge on the distribution of crops
- Validation
    - Run the regional groundwater flow models for the appropriate aquifers using recharge generated the recharge model
    - Compare time series of modelled wadi outflows with observed data
    - Compare recharge time series at selected sites with groundwater hydrographs

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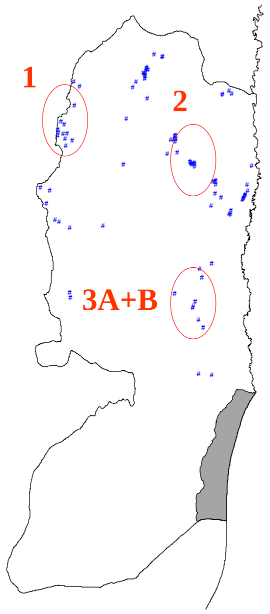
Appendix 1 – Hydrograph analysis

Mountain Aquifer: Groundwater Level Hydrograph Analysis

Groundwater level hydrographs

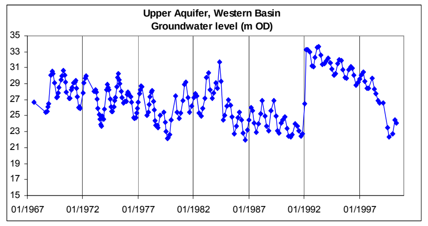
There are at least 90 boreholes in the Mountain Aquifer for which at least some groundwater level hydrographs are available. These boreholes are spread across the Upper and Lower aquifers in all 3 aquifer basins, although there are no hydrographs for the south of the aquifer. The oldest groundwater level records date from 1967, and for most of the boreholes, groundwater levels have been recorded monthly or two-monthly.



West Bank, showing boreholes with groundwater level hydrograph data, and locations of hydrograph groups discussed below

Groundwater hydrographs from 53 boreholes in the Upper and Lower Aquifers have been analysed, mainly for the Western and Eastern Basins. The aim of this work was to characterise temporal variations in groundwater levels, and to identify any systematic trends in groundwater level response.

The groundwater level hydrographs were divided into 4 groups based on their overall response, divided between the Upper and Lower Aquifers and the Eastern and Western Basins. Not all the studied hydrographs were easily classified into groups, and there are a number of anomalous hydrographs. The adjacent charts show a typical hydrograph from each group



1

The largest group of boreholes with available hydrographs is in the Upper Aquifer in the Western Basin. All 20 hydrographs in this group show very similar responses, illustrated by the typical hydrograph in the chart to the left:

•Generally pronounced annual groundwater level fluctuations, with a well-defined but small seasonal response of 2 to 3 m on average

•A consistent timing of groundwater level rises and recessions in all boreholes

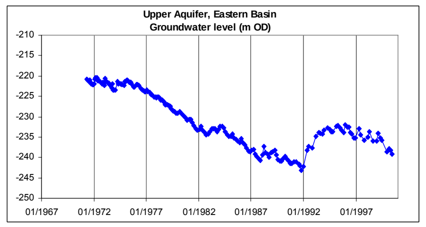
•Four overall temporal trends are obvious:

1968-79 Slow, gentle decline in groundwater levels (GWLs)

1979-84 Gradual increase in GWLs (or standstill in a few cases)

1985-91 Slow, gentle decline in GWLs, punctuated by a large GWL rise in 1991-92 to levels higher than previously recorded

1992-00 Steeper decline in GWLs, intensifying in 1998



2

Only 8 boreholes in the Upper Aquifer in the Eastern Basin had long enough hydrographs to analyse. All but 1 of these show similar responses and are classified as a single group. The chart to the left shows a typical hydrograph response:

•Small annual GWL fluctuations of 2 to 3 m on average

•A consistent timing of GWL rises and recessions.

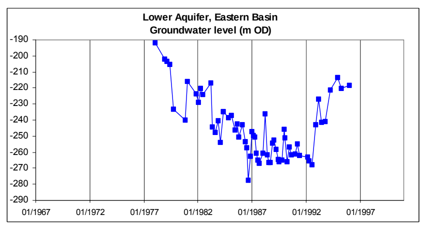
•Four overall temporal trends are obvious:

early 1970s-91 A long term decline in GWLs, punctuated by temporary GWL rises in 1983-84 and 1988-89

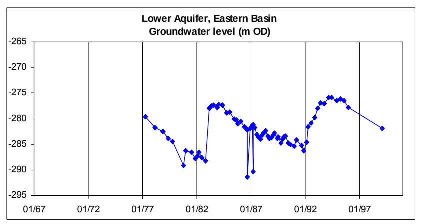
1991-92 A large GWL rise, but not recovering to early 1970s levels

1992-at least 1995 Relatively stable GWLs

1995-00 A return to GWL decline at similar rates to pre-1991



3A



3B

The 12 borehole hydrographs for the Lower Aquifer in the Eastern Basin fall into 2 groups, with 1 anomaly.

•The boreholes in the first group (above left) show a very spiky response, with average annual GWL fluctuations of 15 to 20 m, and a consistent timing of GWL rises and recessions. Three overall temporal trends are obvious:

1981-86 A steep GWL decline

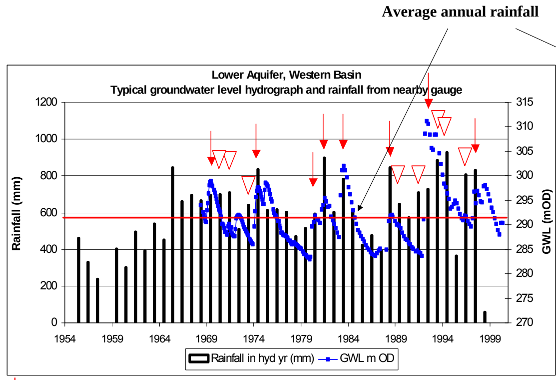
1987-91 Relatively constant GWLs (although large annual fluctuations)

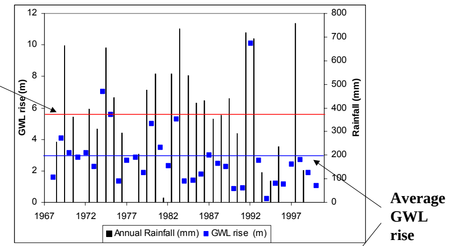
1991-95 A steep GWL rise

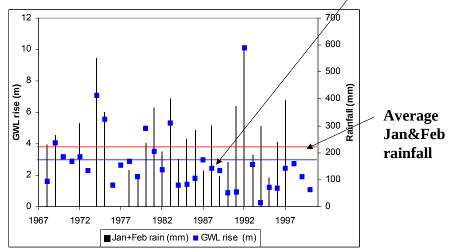
•The boreholes in the second group (above right) show a smoother response, with smaller annual fluctuations of 2 to 4 m on average. The hydrographs show a repeating pattern of a relatively steep GWL decline punctuated by a sharp GWL rise bringing levels back to the starting point. The GWL rise in 1991-92 is not as sharp as that in 1981-82

Groundwater levels and rainfall

Hydrographs for boreholes for which there are nearby (within 2 to 5 km) long term rainfall records were chosen and the relationship between groundwater levels and rainfall analysed. The relationship between rainfall and groundwater level rise is causal, but not always direct or obvious. The analysis has allowed two main observations on groundwater level-rainfall relationships, which help us to understand groundwater recharge processes.







years where high rainfall and large groundwater level rises coincide

years of high rainfall where groundwater level rises are average or below

Relationship between seasonal rainfall and GWL rise

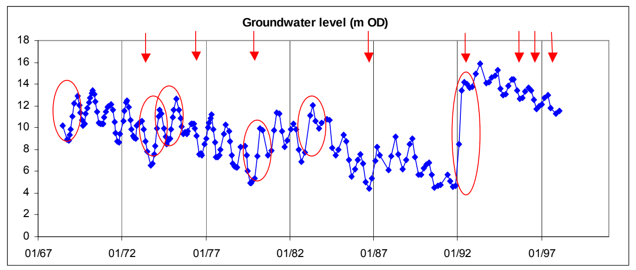
Although large (-r than average) groundwater level rises virtually always occur in years of high (-er than average) rainfall, not all years of high rainfall cause large groundwater level rises (above left). The effect of the timing of winter rainfall was examined by summing rainfall over two successive months and analysing the correlation between large groundwater level rises in a hydrological year and high rainfall in any two month period during the winter of that year. For a number of hydrographs, there is a slightly better correlation between large groundwater level rises, and the combined rainfall in January and February, than there is between groundwater level rises and either total annual rainfall, or the combined rainfall for any other 2 month period of rain. The charts above right show annual groundwater level rise plotted against: total annual rainfall (top) and combined January and February rainfall for a typical hydrograph in the Lower Aquifer, Western Basin.

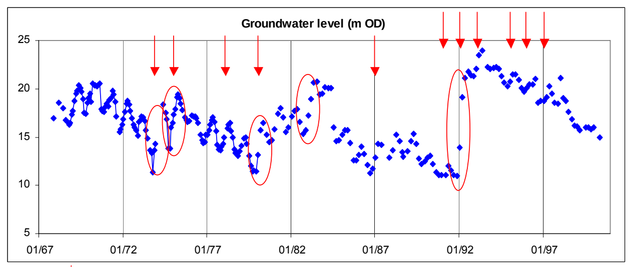
Relationship between rainfall intensity and GWL rise

The availability of daily rainfall series allows more detailed study. Initial analysis suggests that there may be a correlation between rainfall intensity (measured as the amount of rainfall in a single day) and large groundwater level rises.

Charts (right) show typical hydrographs for boreholes in the Upper (top) and Lower Aquifers in the Western Basin, showing that many of the years in which there are large groundwater level rises coincide with years in which there is at least 1 day with more than 70 mm rain.

Interestingly, in most rainfall series examined, the winter of 1991-92 (which saw the largest annual groundwater level rise on record in most boreholes in the Mountain Aquifer) showed the most days with more than 70 mm rain.





years in which there is at least 1 day with more than 70 mm rain

years in which there are larger than average groundwater level rises

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B É Ó Dochartaigh, British Geological Survey, 2003.

Appendix 2 – Description of SCS D-Hydrographs

Synthetic Hydrograph

Synthetic hydrographs are estimated based on the measures of the catchment characteristics. They have a triangular shape whose shape is determined by the time to peak T_p, the Peak runoff Q_p and the time base T_B as shown in Figure X1.

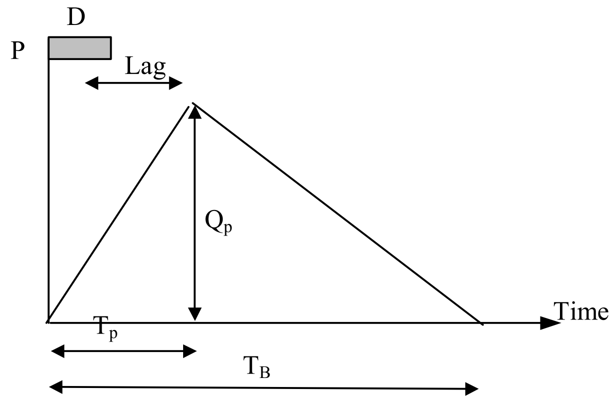


Figure X1: P mm, D hour synthetic unit hydrograph from SCS, USA after Chadwic et al. 1986

The parameters controlling the precipitation P (mm), duration D (hour) of the synthetic unit hydrograph derived by the US Soil Conservation Service (USCS) are given by:

$T_p = lag + \frac{D}{2}$ in minutes

$Q_p = 0.208AP/T_p$ in m^3/sec

$T_B = 2.67T_p$ in minutes

where *lag* is the lag time and is given by:

$lag = 0.6t_c$

The time of concentration t_c is given by the following equation:

$t_c = \left(\frac{1}{52}\right)\left(\frac{L^3}{H}\right)^{0.385}$ in minutes

where:

- L is the stream length in metre
- H is the difference in ground elevation between the start of the stream and the gauging location in metre.

The unit hydrograph is used to predict the surface runoff for any storm event by the process of convolution. However, the generated unit hydrograph can be directly used if the storm duration and intensity matches the values detemined by the above equations. The total storm volume V is given in this case by the following equation:

$V = 0.5(Q_p * T_B)$ in m^3 if Q_p is in m^3/sec and T_B is in seconds

Appendix 3 – Relationship of model grid with GIS grid

Summary of differences between GIS grid and model grid

The model grid is set up by specifying the X and Y co-ordinates of the top left hand corner. The position of the node in the top left hand corner is then calculated using the grid spacing in the X and Y direction. The node is set half a grid spacing in both directions.

Gridded data from a GIS is used to provide an input to the model. Therefore, the relationship between the GIS grid and the model grid needs to be determined. The two grids are presented in Figure 1. The model grid, shown in red, is offset by half a grid spacing from the GIS grid, shown in black. The grids are defined by different origins:

- Origin of GIS grid is Y_{ll}, X_{ll}
- Origin of model grids is Y_{tl}, X_{ll}

It is necessary to define a relationship to convert the origin of the GIS grid to the origin of the model grid.

Therefore to transcribe the co-ordinates used by the GIS (X and Y for the lower left hand corner) and that used by the model (X and Y for the top left hand corner) the following relationship is used:

$$Y_{tl\ (GIS)} = (n_{rows} - 1).\Delta Y + Y_{ll\ (GIS)}$$

And so considering the top of the model is a full grid spacing above the node, the Y co-ordinate of the boundary of the recharge model is given by:

$$Y_{tl\ (MODEL)} = Y_{ll\ (GIS)} + \Delta Y = (n_{rows} - 1).\Delta Y + Y_{ll\ (GIS)} + \Delta Y$$

Which simplifies to:

$$Y_{tl\ (MODEL)} = n_{rows}.\Delta Y + Y_{ll\ (GIS)}$$

Therefore to convert the X and Y co-ordinates from the GIS grid to the model grid, then the Y co-ordinate is modified using the following relationship:

$$Y_{node} = Y_{tl\ (MODEL)} - (i_{rows} - 1).\Delta Y - 0.5\Delta Y$$

The X co-ordinates are offset by half a grid spacing for each node (i.e. add $0.5\Delta x$).

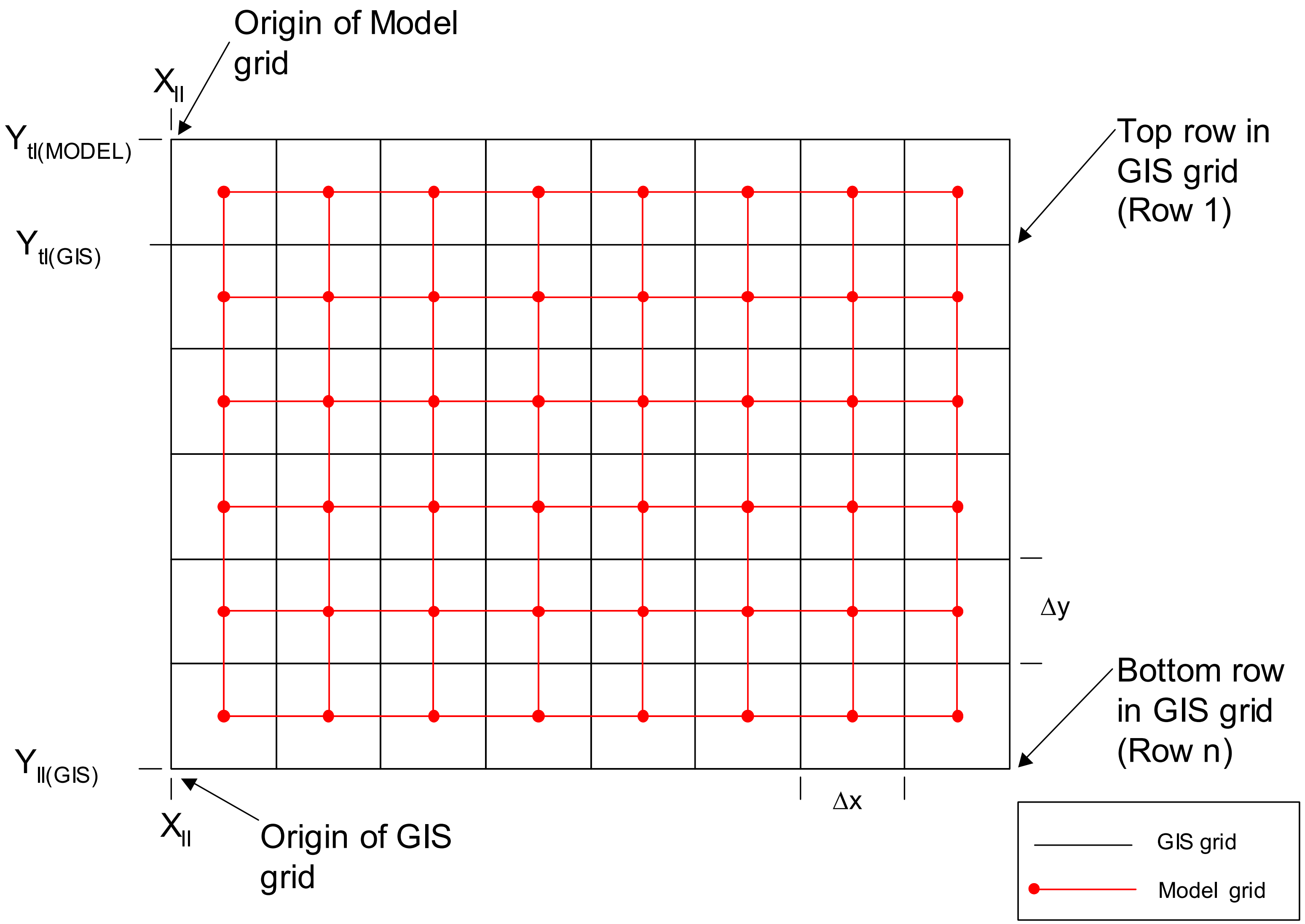
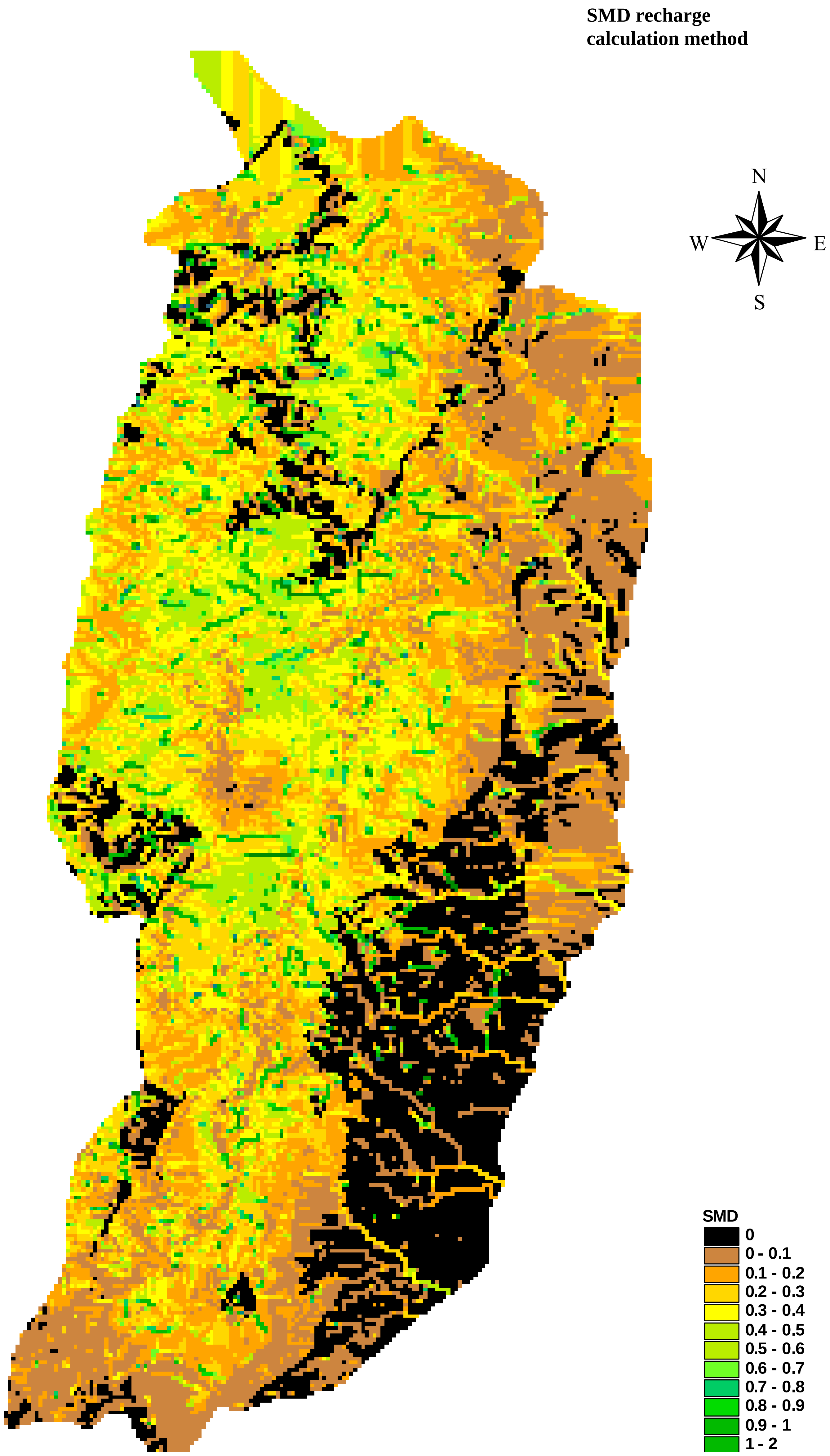
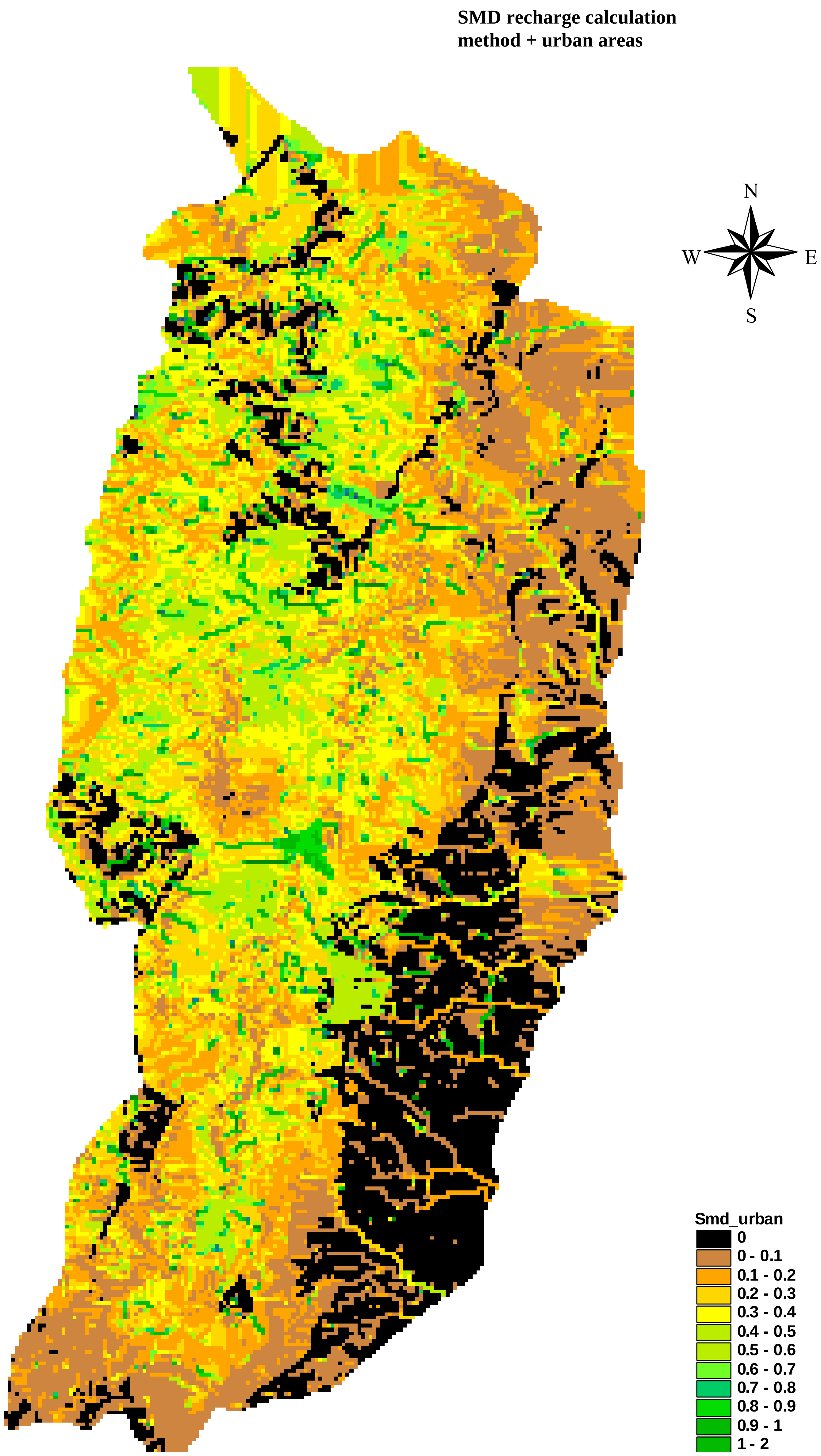
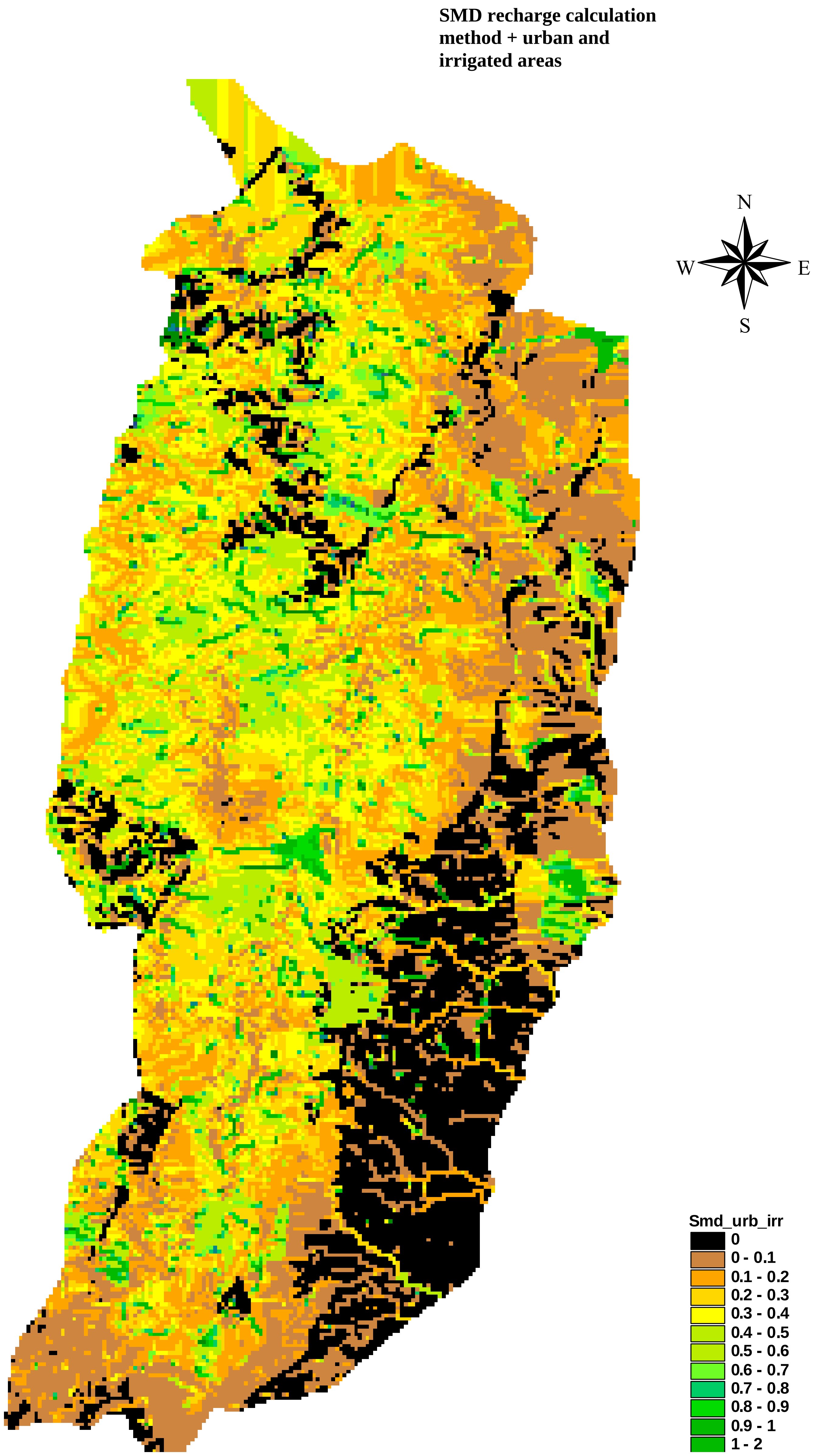


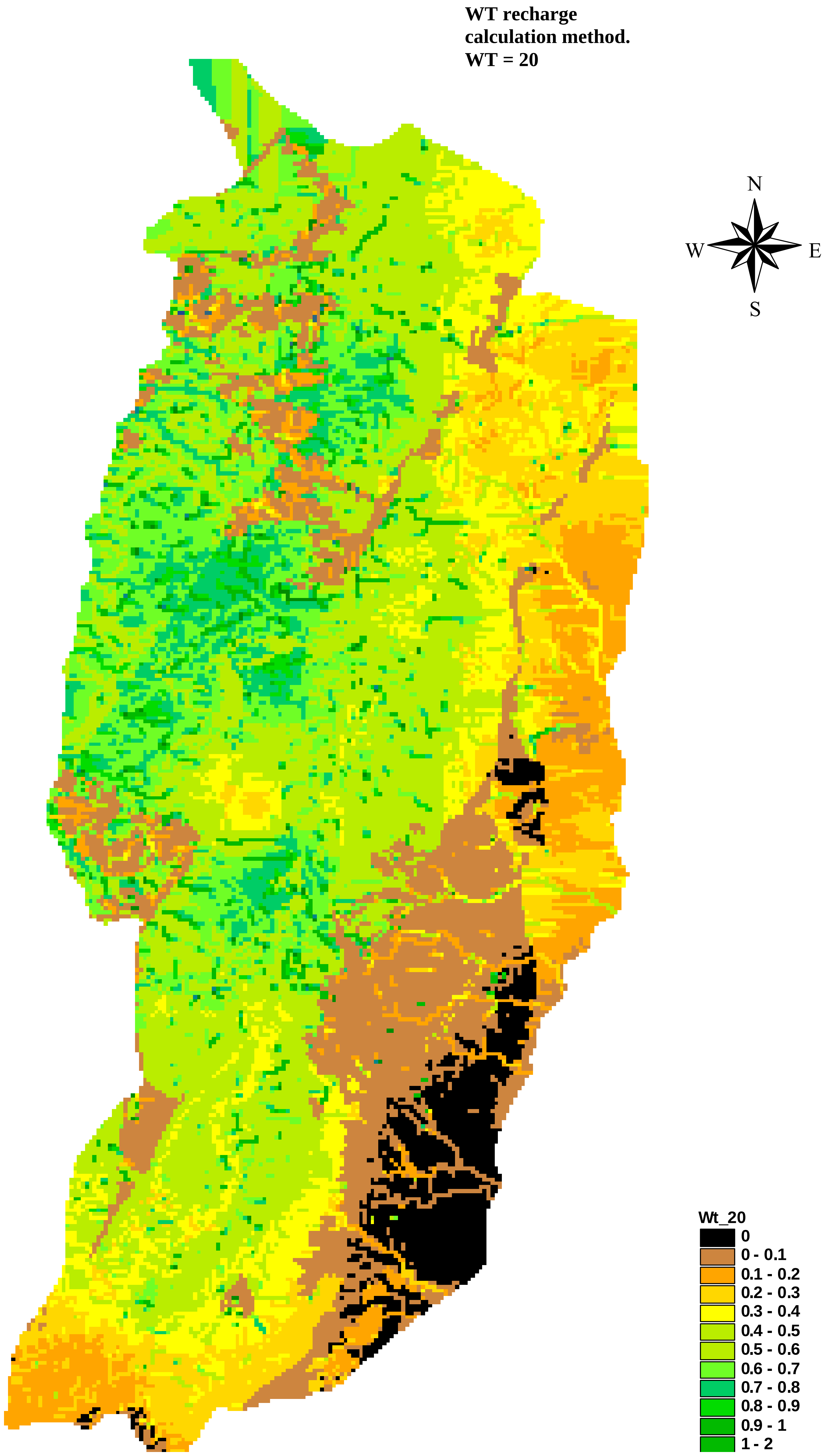
Figure 1 Relationship between GIS grid and model grid.

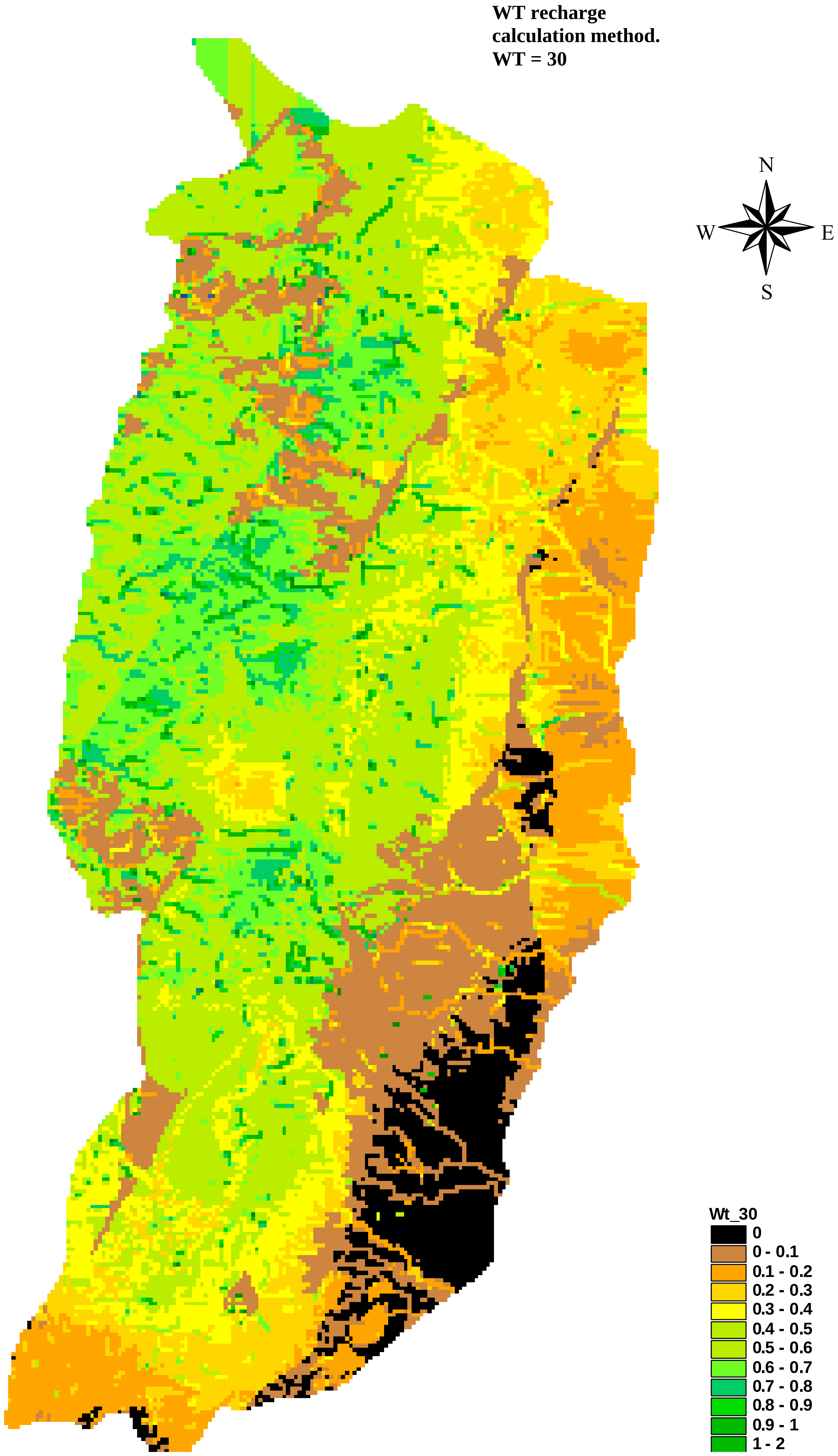
Appendix 4 – Model output for the West Bank recharge model

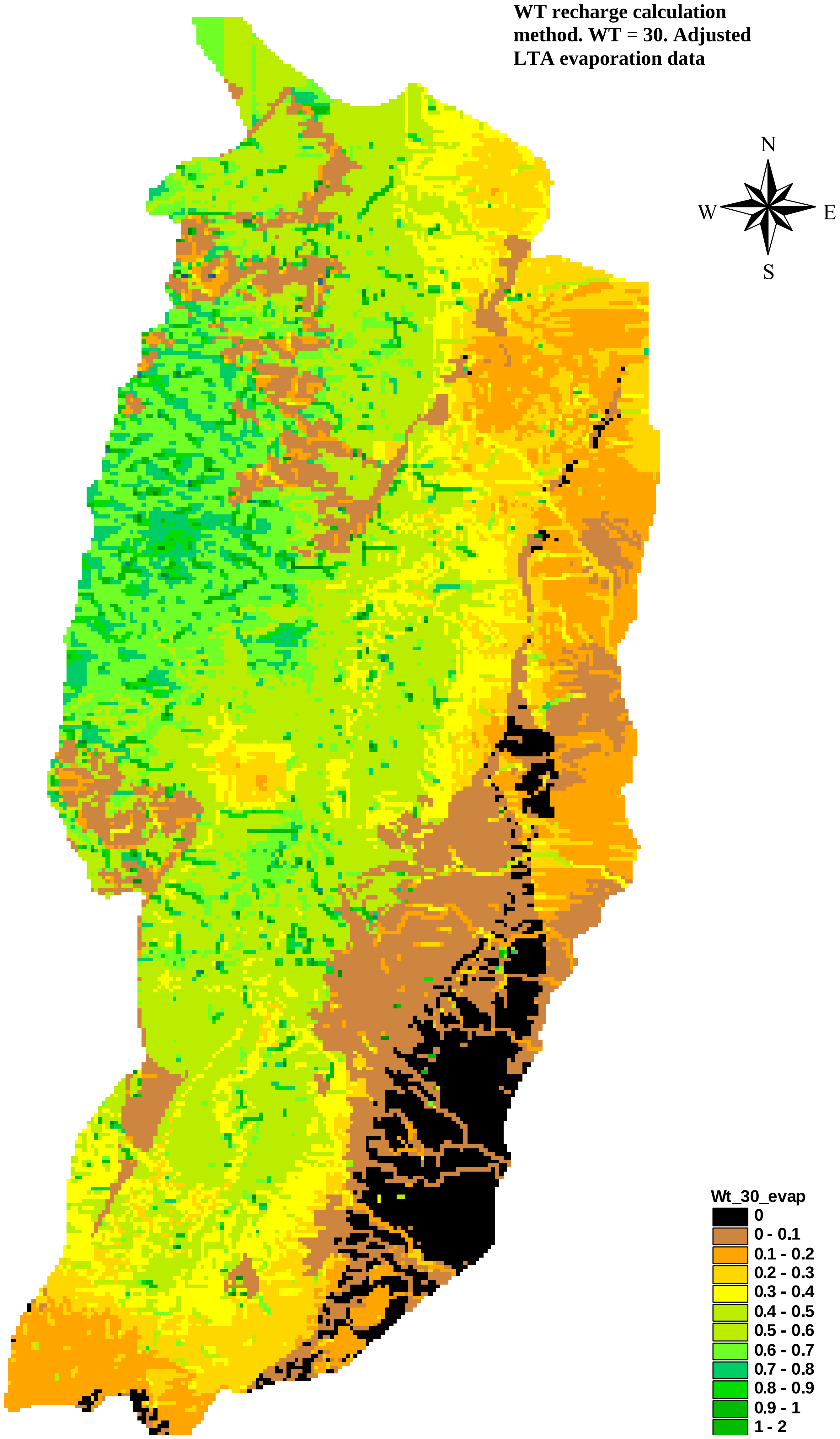

SMD recharge
calculation method
N
W
E
S
SMD
0
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
1 - 2


SMD recharge calculation
method + urban areas
N
W
E
S
Smd_urban
0
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
1 - 2

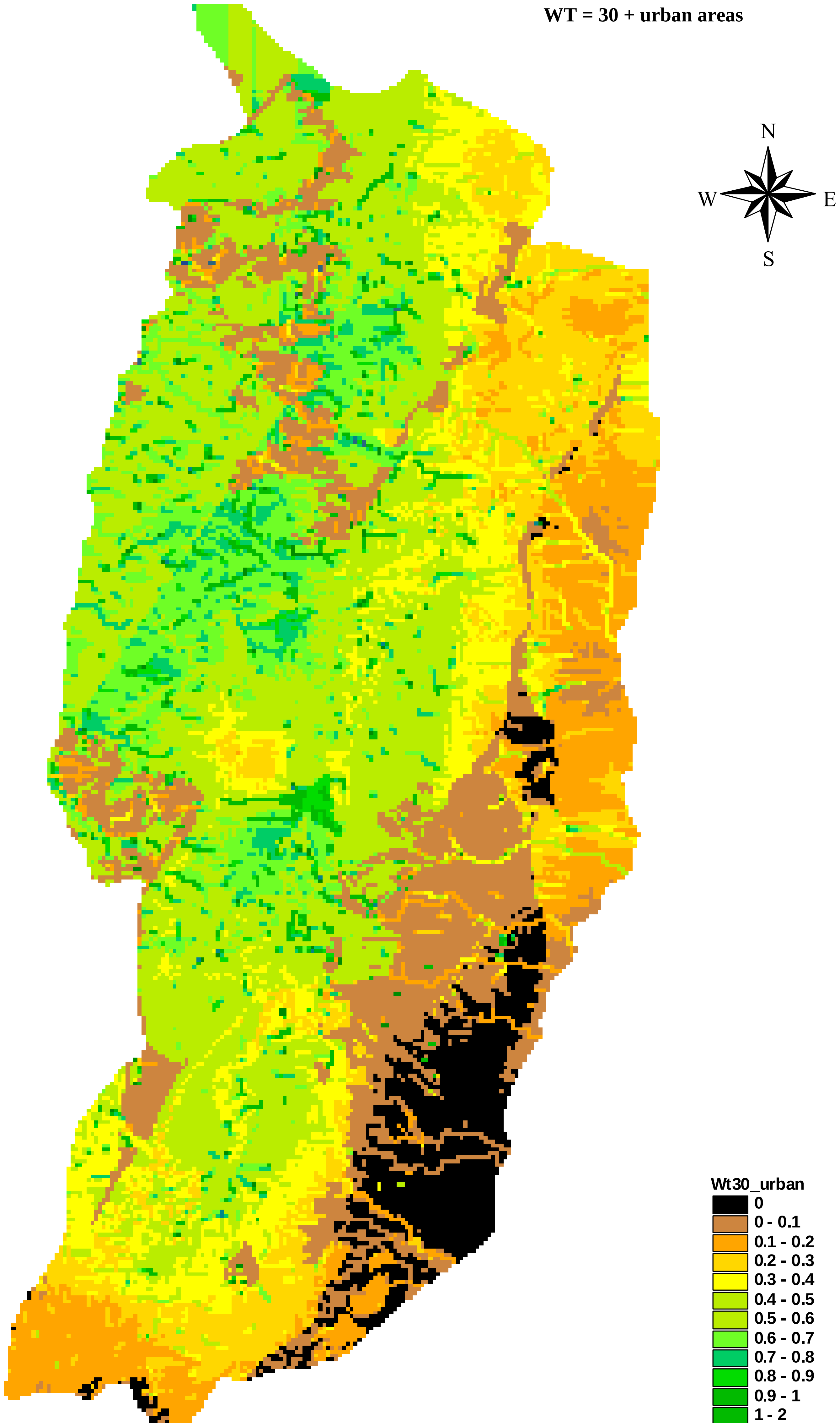

SMD recharge calculation method + urban and irrigated areas
N
W
E
S
Smd_urb_irr
0
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
1 - 2

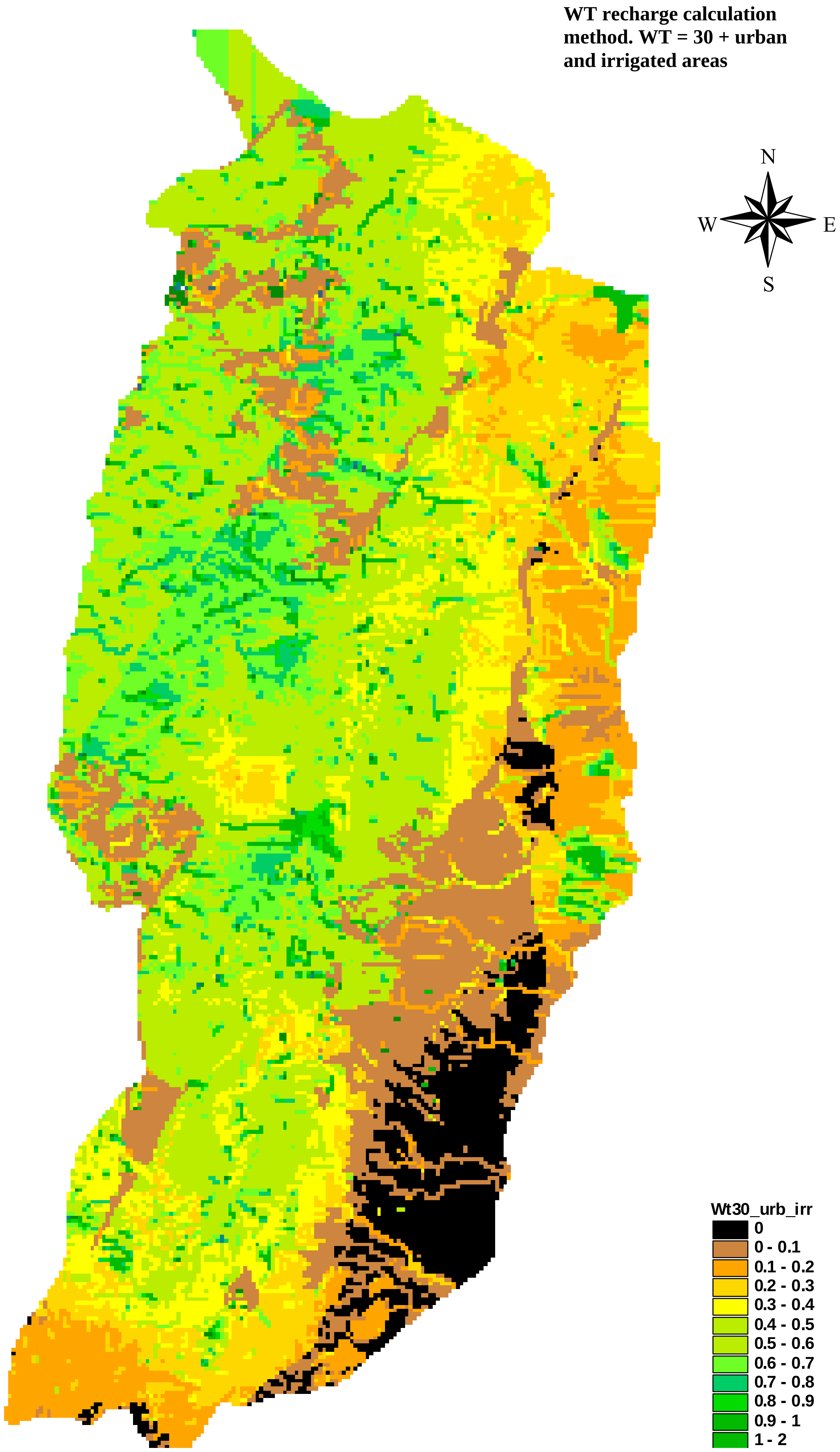

WT recharge
calculation method.
WT = 20
N
W
E
S
Wt_20
0
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
1 - 2

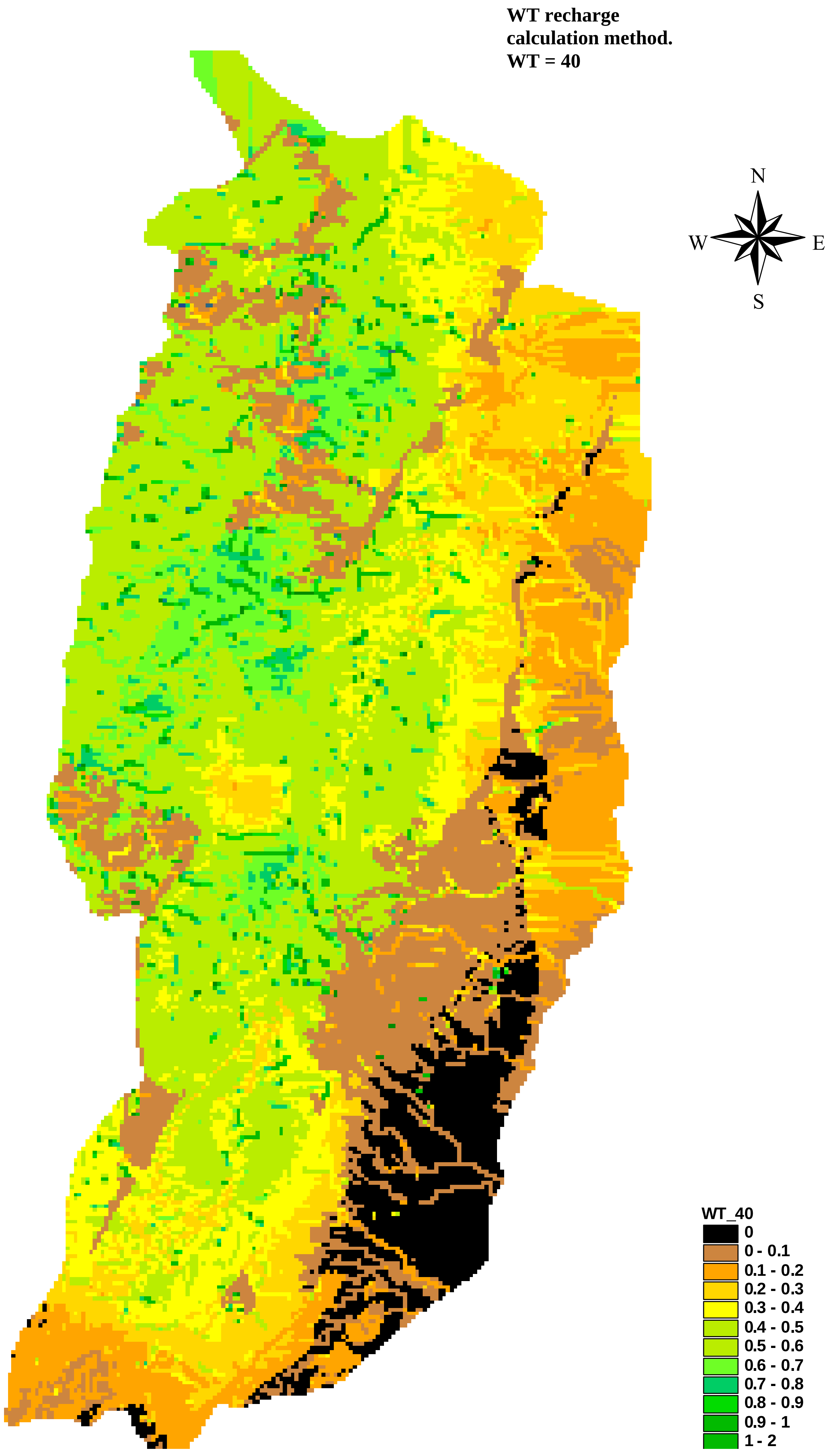

WT recharge
calculation method.
WT = 30
N
W
E
S
Wt_30
0
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
1 - 2


WT recharge calculation method. WT = 30. Adjusted LTA evaporation data
N
W
E
S
Wt_30_evap
0
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
1 - 2

WT recharge calculation method. WT = 30 + urban areas




WT recharge calculation method. WT = 30 + urban and irrigated areas
N
W
E
S
Wt30_urb_irr
0
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
1 - 2


WT recharge
calculation method.
WT = 40
N
W
E
S
WT_40
0
0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1
1 - 2