# Vulnerability Mapping for the Protection of Carbonate (Karst) Aquifers (Ramallah-Al Bireh District)

Eng. Amjad Assi

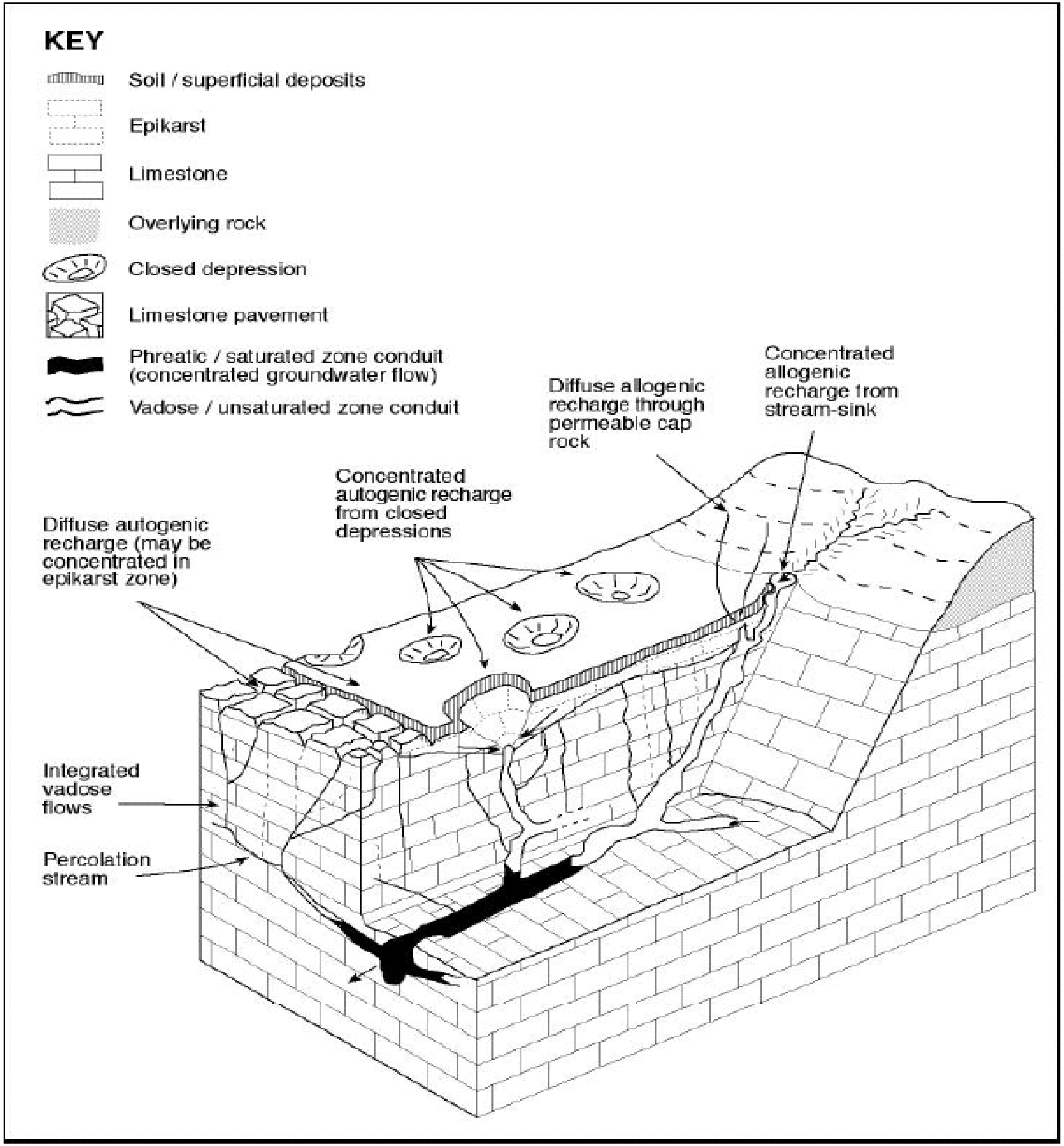
House of Water and Environment

May, 2007

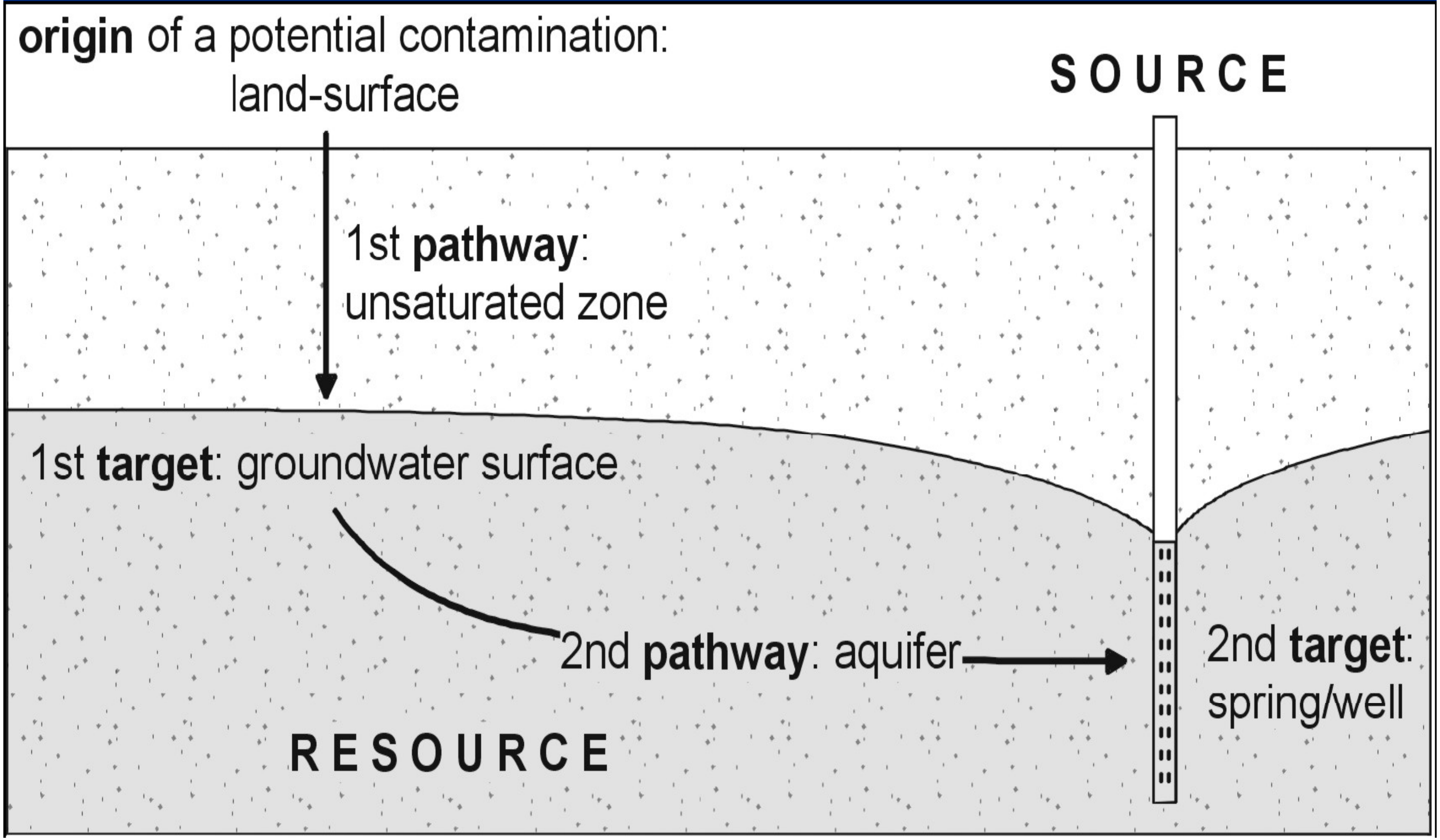
# INTRODUCTION

- Water resources are vitally important for the future of humankind.
- Groundwater from karst aquifers is among the most important drinking water resource in the West Bank.
- The protection of groundwater within karst aquifers to assure its quality for potable use should be one of the Palestinians priorities.
- The term 'vulnerability' is not restricted to groundwater but is used in a wide sense to describe the sensitivity of whatever to any kind of stress.
- The aim from this lecture is to present an integrated method that addresses the question of groundwater vulnerability and risk in karst environments.

# Conceptual Model of a Karst Aquifer

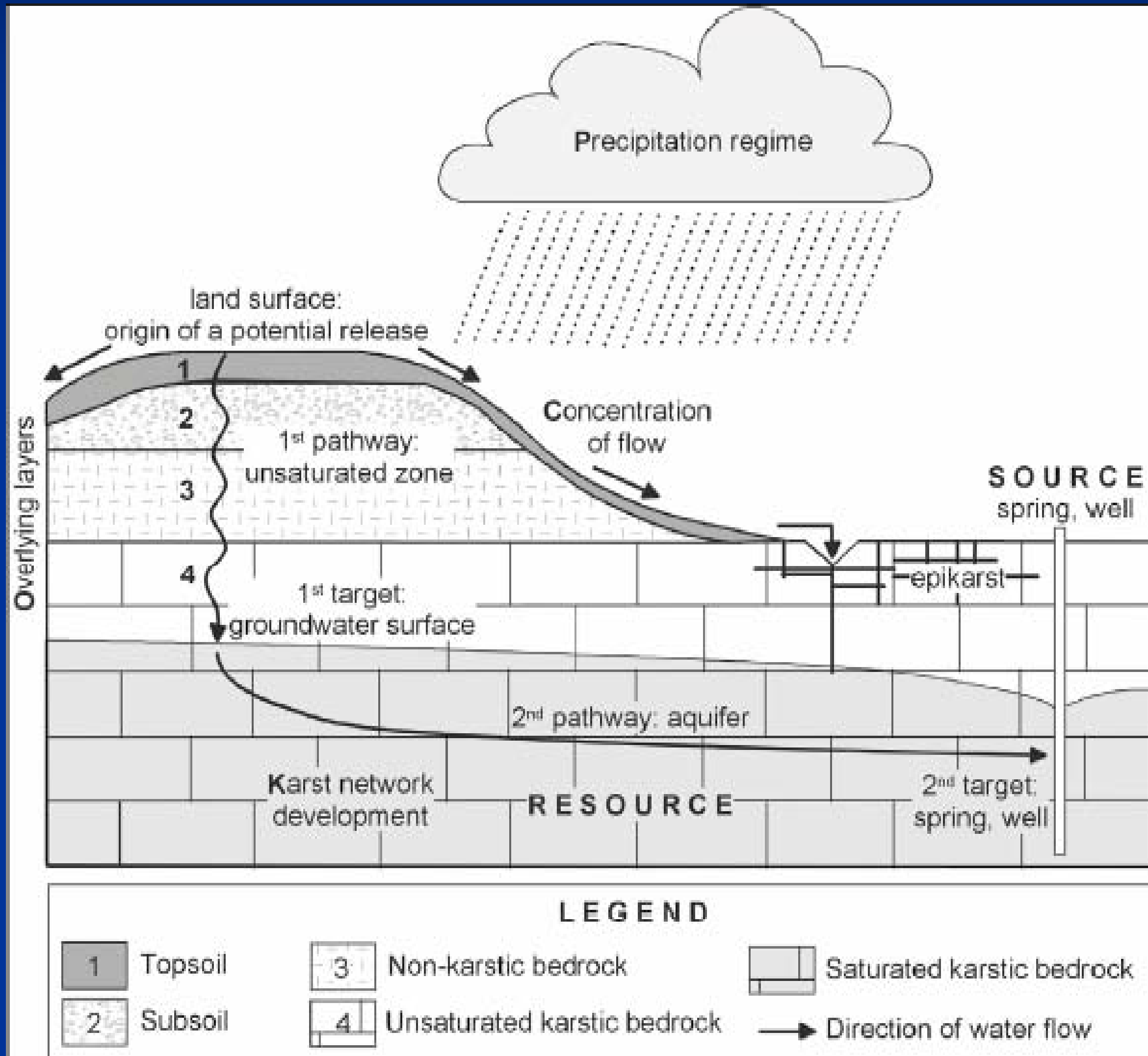


# The Origin-Pathway-Target Model



# General Concept of the PI Method

- It is a GIS-based approach.
- It is based on an origin-pathway-target model.



# PI - Method

## (P) – Protective Cover

- Thickness,
- Hydraulic Conductivity,
- Degree of Karstification,
- Joints / faults.

## ( I ) – Infiltration Conditions

- Type of infiltration,
- Flow concentration and degree of by-passing the protective cover.

- **P- Factor:** the effectiveness of the production cover above the groundwater table.
- **I- Factor**: reduction of the protection cover by the bypassing flow.

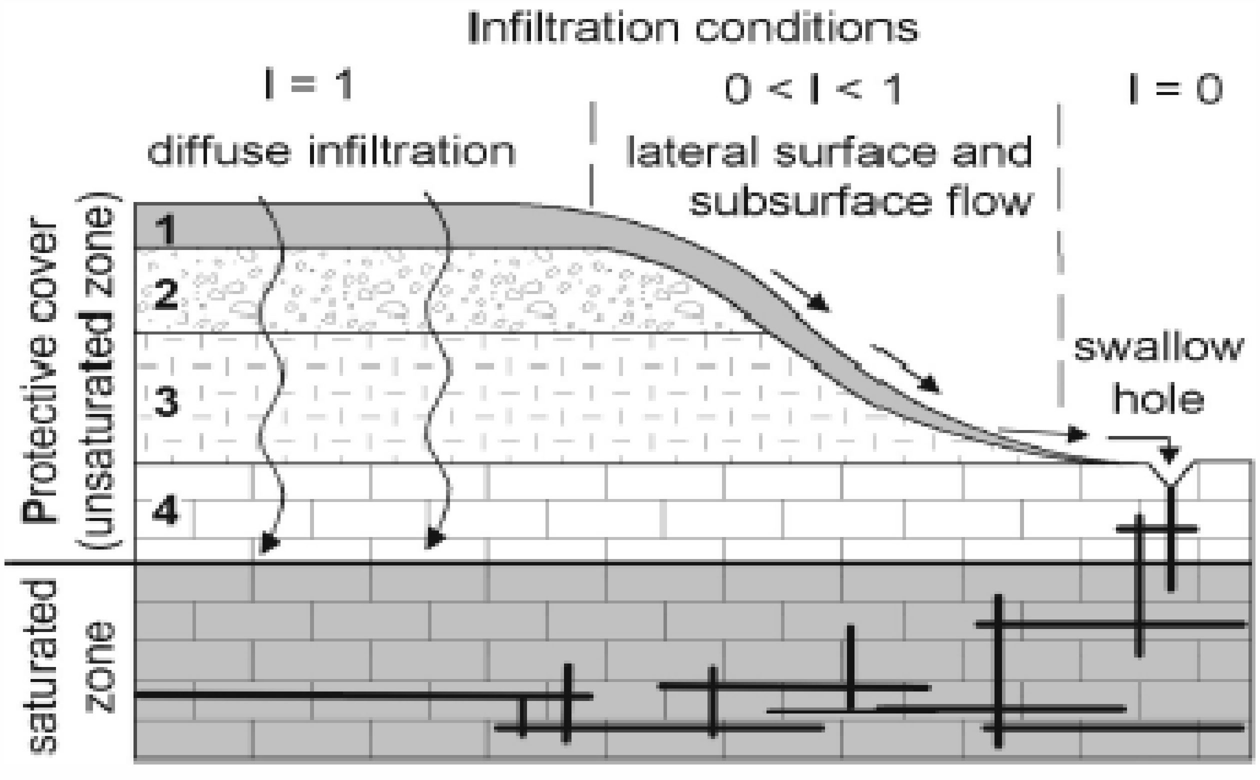


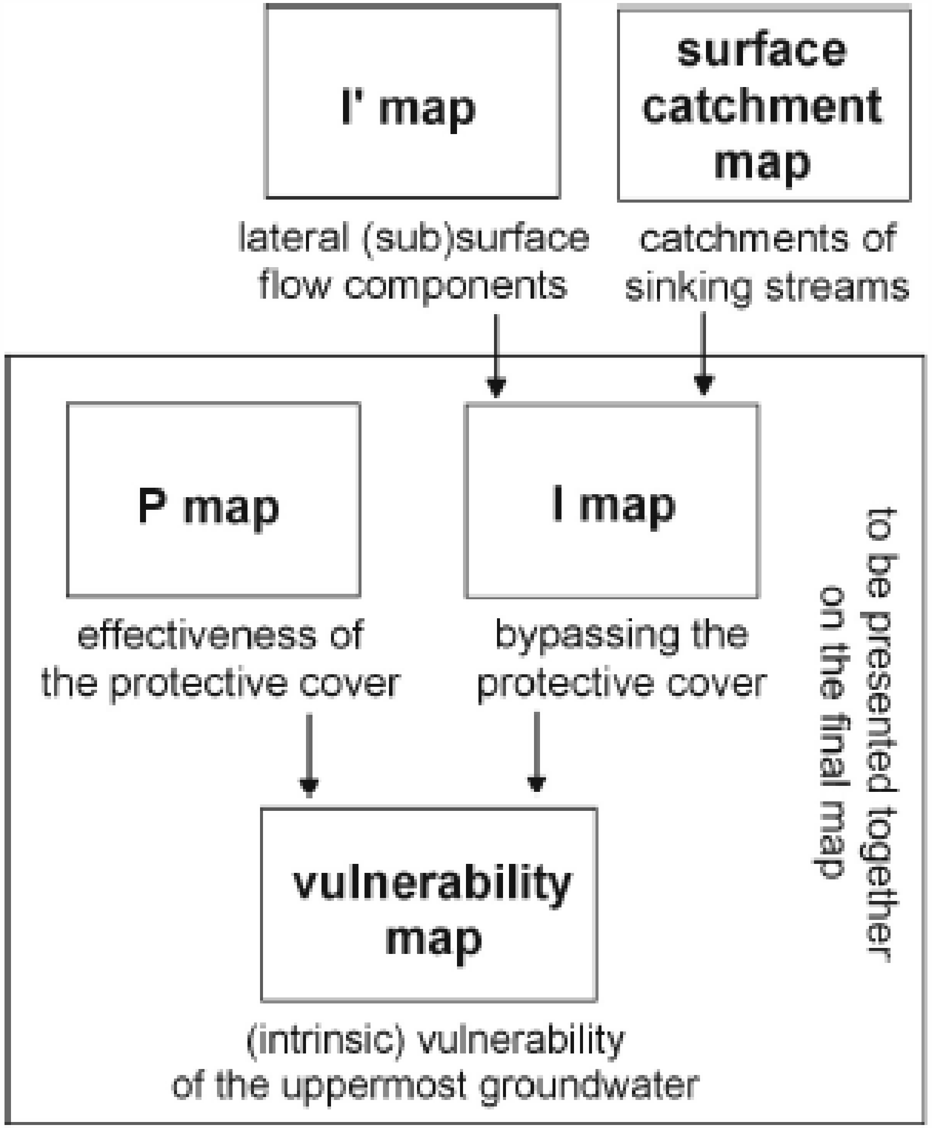

Fig. 42: Illustration of the PI method: The P factor takes into account the effectiveness of the protective cover as a function of the thickness and hydraulic properties of all the strata between the ground surface and the groundwater surface. The protective cover consists of up to four layers: 1. topsoil, 2. subsoil, 3. non karst rock, 4. unsaturated karst rock. The I factor expresses the degree to which the protective cover is bypassed by lateral surface and subsurface flow, especially within the catchments of sinking streams.

# Simple Flow Chart for the PI Method

**The vulnerability map** is obtained by intersecting the *P map* with the *I map*.

**The P map** shows the effectiveness of the productive cover as a function of the thickness and permeability of all the strata above the ground water surface.

**The I map** shows the degree to which the protective cover is bypassed. It is obtained by intersecting the map showing the catchment areas of the sinking streams with the so-called **I' map**, which shows the distribution of lateral, surface and subsurface flow.



# P-Map

### Topsoil - T

| eFC [mm] up to 1 m depth | T |
|---|---|
| > 250 | 750 |
| > 200-250 | 500 |
| > 140-200 | 250 |
| > 90-140 | 125 |
| > 50-90 | 50 |
| < 50 | 0 |

### Recharge - R

| Recharge [mm/y] | R |
|---|---|
| 0-100 | 1.75 |
| >100-200 | 1.50 |
| >200-300 | 1.25 |
| >300-400 | 1.00 |
| >400 | 0.75 |

### Subsoil - S

| Type of subsoil (grain size distribution) | S | Type of subsoil (grain size distribution) | S |
|---|---|---|---|
| clay | 500 | very clayey sand, clayey sand, loamy silty sand | 140 |
| loamy clay, slightly silty clay | 400 | | |
| slightly sandy clay | 350 | sandy silt, very loamy sand | 120 |
| silty clay, clayey silty loam | 320 | loamy sand, very silty sand | 90 |
| clayey loam | 300 | slightly clayey sand, silty sand, sandy clayey gravel | 75 |
| very silty clay, sandy clay | 270 | | |
| very loamy silt | 250 | slightly loamy sand, sandy silty gravel | 60 |
| slightly clayey loam, clayey silty loam | 240 | slightly silty sand, slightly silty sand with gravel | 50 |
| very clayey silt, silty loam | 220 | sand | 25 |
| very sandy clay, sandy silty loam, slightly sandy loam, loamy silt, clayey silt | 200 | sand with gravel, sandy gravel | 10 |
| | | gravel, gravel with breccia | 5 |
| sandy loam, slightly loamy silt | 180 | non-lithified volcanic material (pyroklastica) | 200 |
| slightly clayey silt, sandy loamy silt, silt, very sandy loam | 160 | peat | 400 |
| | | sapropel | 300 |

### Lithology - L

| Lithology | L |
|---|---|
| claystone, slate, marl, siltstone | 20 |
| sandstone, quarzite, volcanic rock plutonite, metamorphite | 15 |
| porous sandstone, porous volcanic rock (e.g. tuff) | 10 |
| conglomerate, breccia, limestone, dolomitic rock, gypsum rock | 5 |

### Fracturing - F

| Fracturing | F |
|---|---|
| non-jointed | 25.0 |
| slightly jointed | 4.0 |
| moderately jointed, slightly karstified or karst features completely sealed | 1.0 |
| moderately karstic or karst features mostly sealed | 0.5 |
| strongly fractured or strongly karstified and not sealed | 0.3 |
| Epikarst strongly developed, not sealed | 0.0 |
| not known | 1.0 |

**Thickness of each stratum in [m] - M**

**Bedrock - B**
$B = L \cdot F$

**Artesian pressure A**
1500 points

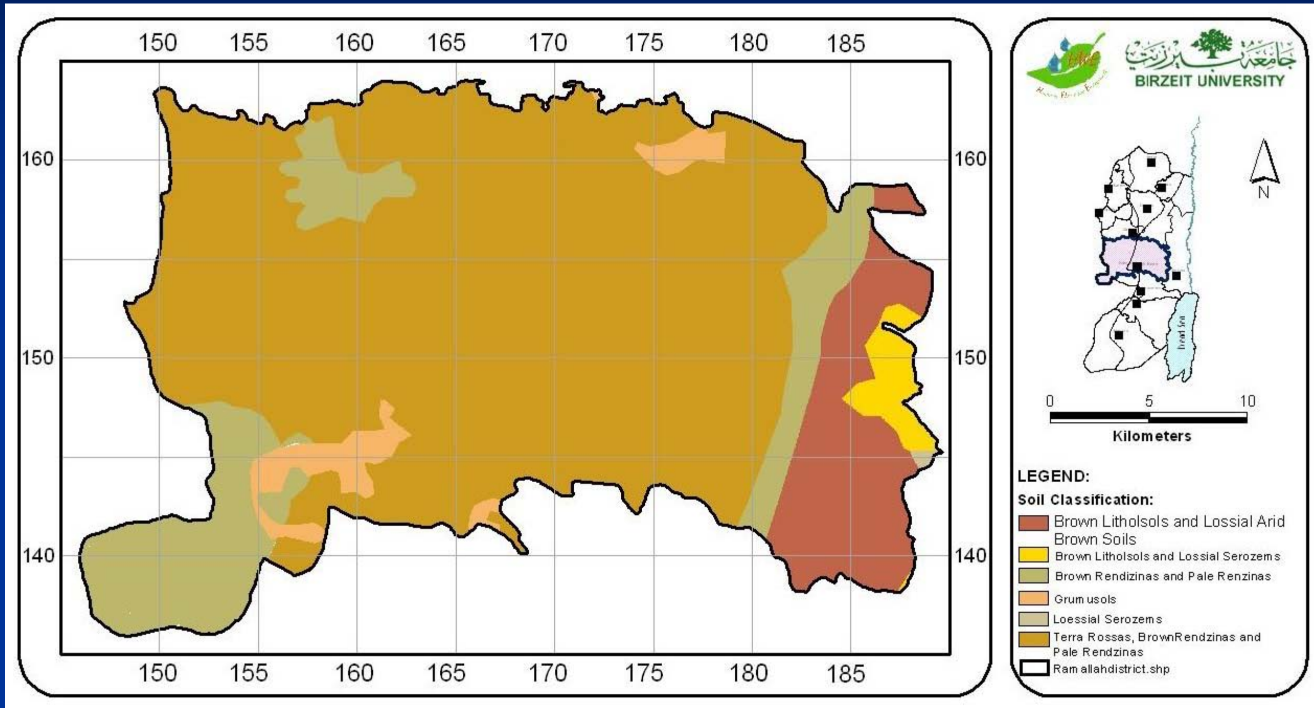
**Total protective function P$_{TS}$**

$$P_{TS} = \left[ T + \left( \sum_{i=1}^{m} S_i \cdot M_i + \sum_{j=1}^{n} B_j \cdot M_j \right) \right] \cdot R + A$$

| score $P_{TS}$ | effectiveness of protective cover | **P-factor** | example |
|---|---|---|---|
| 0-10 | very low | **1** | 0-2 m gravel |
| >10-100 | low | **2** | 1-10 m sand with gravel |
| >100-1000 | medium | **3** | 2-20 m slightly silty sand |
| >1000-10000 | high | **4** | 2-20 m clay |
| >10000 | very high | **5** | > 20 m clay |

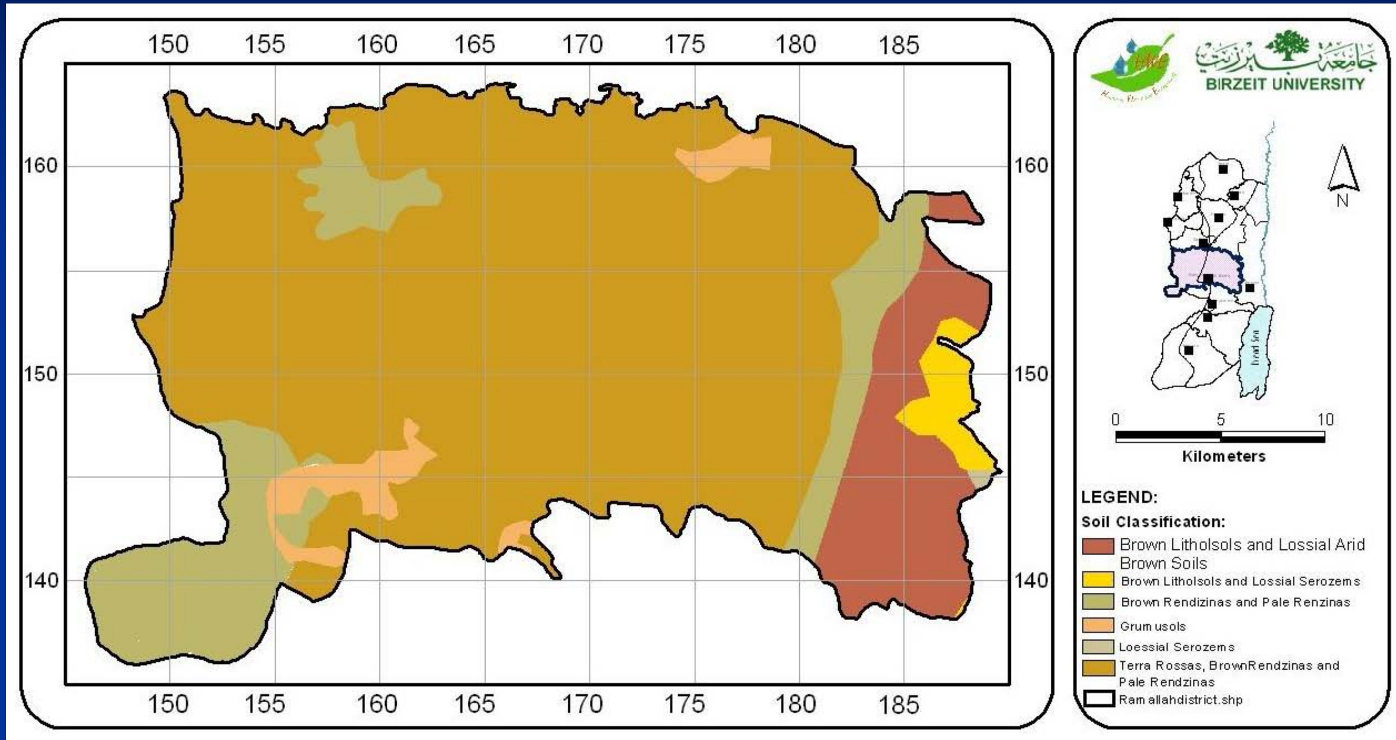
**P-map**

# Top Soil – (T-Factor)




| Soil type | Measured / Estimated FC (mm/m) | Weighted Value (T) |
|---|---|---|
| Terra Rossa, Brown Rendzinas and Pale Rendzinas | 446 | 750 |
| Brown Rendzinas and Pale Rendzinas | 334 | 750 |
| Grumusols | 460 | 750 |
| Brown Lithosols and Loessial Serozems | 90-140 | 125 |
| Brown Lithosols and Loessial Arid Brown Soil | 140-200 | 250 |
| Loessial Serozems | 140-200 | 250 |

# Sub-soil (S-Factor)




| Soil type | Sub-soil type | Weighted Value (S) |
|---|---|---|
| Terra Rossa, Brown Rendzinas and Pale Rendzinas | Clay | 500 |
| Brown Rendzinas and Pale Rendzinas | Clayey loam | 300 |
| Grumusols | Clay | 500 |
| Brown Lithosols and Loessial Serozems | Slightly clayey sand | 75 |
| Brown Lithosols and Loessial Arid Brown Soil | Loamy | 250 |
| Loessial Serozems | Slightly clay | 320 |

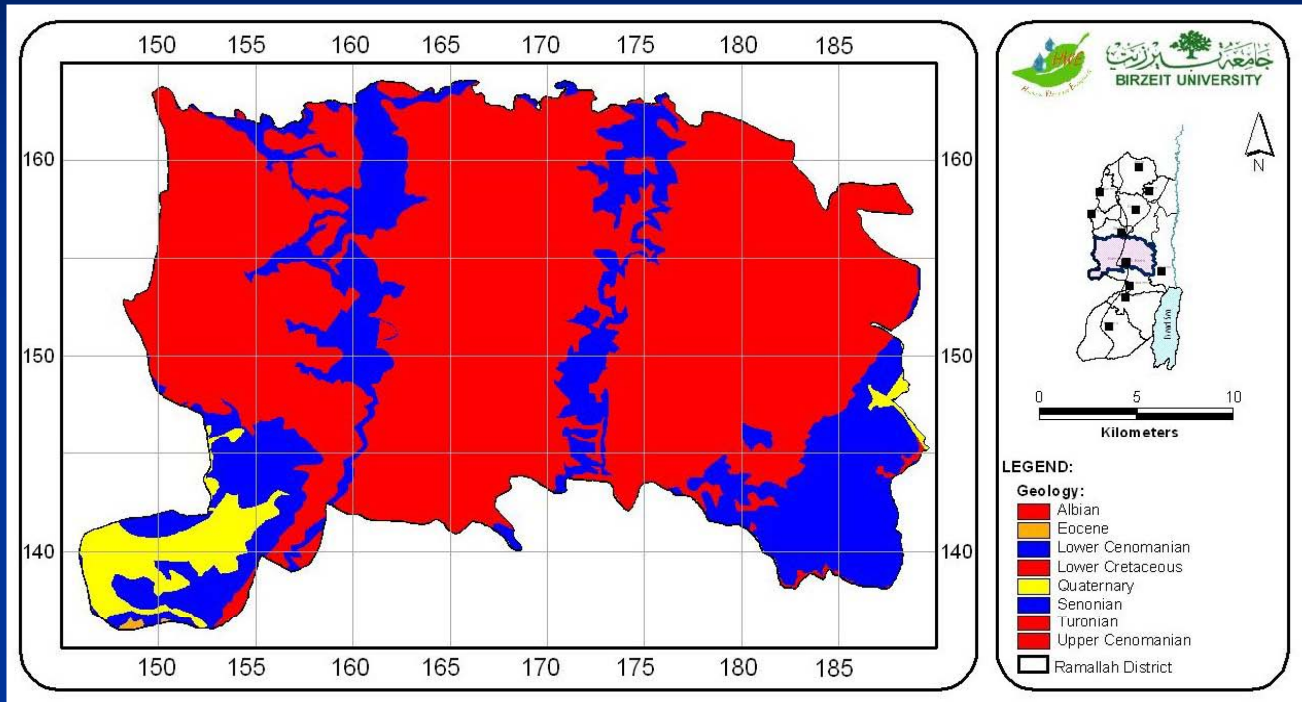
| Period | | Age | | Graphic Log | Typical Lithology | Formation (West Bank Terminology) | Sub-Formation | Group | Symbol | | Formation (Israeli Terminology) | Hydro-stratigraphy | Typical Thickness (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quaternary | | Holocene | | | Marl (surface crust) and alluvium Gravels and fan deposits | Alluvium | | - | Qh-a | | Alluvium | Local Aquifer | 0 - 100 |
| | | Pleistocene | | | Thinly laminated marl with gypsum bands and poorly sorted gravel and pebbles | Lisan | | | Qp-l | | Lisan\Kurkar Group | "Aquitard" | 10 - 200 |
| Tertiary | Neogene | Miocene - Pliocene | | | Conglomerates, marl, chalk clay and limestone | Beida | | | Tmp-b | | Saqiye Group | Local Aquifer | 20 - 200 |
| | Paleogene | Eocene (Lower - Middle) | | | Nummulitic reefal Limestone | Jenin | Jenin 4 | Jenin | Te-j | Te-j4 | 'Avedat Group | Aquifer | 90 - 670 |
| | | | | | Nummulitic bedded Limestone | | Jenin 3 | | | Te-j3 | | | |
| | | | | | Nummulitic Limestone,Chalk | | Jenin 2 | | | Te-j2 | | | |
| | | | | | Chalk ,Nummulitic Limestone | | Jenin 1 | | | Te-j1 | | | |
| Cretaceous | | Paleocene | | | Marl,Chalk | Khan Al-Ahmar | | Nablus | Ks-n | Ks-ka | Mt.Scopus Group | Aquitard (Local Aquifer) | 40 - 150 |
| | Upper | Senonian | Maastrichtian Danian | | Chalk ,Marl | | | | | | | | |
| | | | Campanian | | Main Chert ,Phosphate | Wadi Al-Qilt | | | | Ks-aq | | Aquiclude | 10 - 120 |
| | | | Coniancian-Santonian | | Chalk and Chert | Abu Dis | | | | Ks-ad | | | 0 - 450 |
| | | Turonian | | | White Limestone ,stilolithes | Jerusalem | Upper | Ramallah (West Bank) | Kc-j | Kc-ju | Bina | Upper Aquifer (Mountain Aquifer System) | 40 - 190 |
| | | | | | Limestone and Dolomite | | Middle | | | Kc-jm | | | |
| | | | | | Yellow thin bedded Limestone | | Lower | | | Kc-jl | | | |
| | | Cenomanian | Upper | | Dolomite,soft | Bethlehem | Upper | | Kc-b | Kc-bu | Weradim | | 50 - 210 |
| | | | | | Chalky Limestone,Chalk | | Lower | | | Kc-bl | Kefar Sha'ul | | |
| | | | | | Karstic Dolomite | Hebron | | | Kc-h | | Amminadav | | 65 - 160 |
| | | | Lower | | Yellow marl | Yatta | Upper | | Kc-y | Kc-y2 | Moza | "Aquitard" | 50 - 125 |
| | | | | | Lime & Dolostone,Chalk,(Clay) | | Lower | | | Kc-y1 | Beit Meir | | |
| | Lower | Albian | | | Reefal Limestone | Upper Beit Kahil | UBK2 | | Ka-ubk | Ka-ubk2 | Kesalon | Lower Aquifer | 10 - 20 |
| | | | | | Dolomite Limestone, interbedded with Marl | | UBK1 | | | Ka-ubk1 | Soreq | | 60 - 130 |
| | | | | | Dolomite | Lower Beit Kahil | UBK2 | | Ka-lbk | Ka-lbk2 | Giv'at Ye'arim | | 40 - 90 |
| | | | | | Karstic Limestone | | UBK1 | | | Ka-lbk1 | Kefira | | 100 - 160 |
| | | | | | Marl ,marly nodular Limestone | Qatana | | Kobar | Ka-q | | Qatana | Aquitard | 42 |
| | | | | | Marly Limestone and Limestone | Ein Qinya | | | Ka-eq | | Ein Qinya | Local Aquifer | 55 |
| | | Aptian | | | Shale | Tammun | | | Ka-t | | Tammun | Aquiclude | 300+ |
| | | | | | Shale and Limestone | Ein Al-Assad | | | Ka-ea | | | | 20+ |
| | | | | | Marly Limestone,sandy | Nabi Sa'id | | Kurnub | Ka-ns | | Hatira | Aquifer | 20+ |
| | | Neocomian | | | Sandstone | Ramali | | | Kn-r | | | | 70+ |
| | | | | | Volcanics | Tayasir | | | Kn-t | | | | 35 |
| Jurassic | | Oxfordian | | | Marl interbedded with chalky limestone | Maleh | Upper Maleh | - | Jo-m | Jo-um | 'Arad Group | Aquitard | 100 - 200 |
| | | | | | Dolomitic limestone, jointed and karstic | | Lower Maleh | - | | Jo-lm | | Aquifer | 50 - 100 |

Stratigraphic Section of the West Bank

LEGEND

- Dolomite
- Limestone
- Marl
- Conglomerate
- Megafauna
- Flint concretions
- Chalk
- Nari
- Sandstone
- Volcanics
- Relatively Permeable
- Relatively Impermeable

# Lithology andFracturing (L & F – Factors)




| Lithology | Lithology Value (L) | Fracturing Value (F) |
|---|---|---|
| Nari (surface crust) and alluvium gravels and fan deposits | 5 | 4 |
| Conglomerates, marl, chalk, clay and limestone | 5 | 20 |
| Reefal limestone, Nummulitic limestone and chalk | 5 | 0.5 |
| , chalk and chert | 20 | 25 |
| White limestone, stilolithes dolomite and thin bedded limestone | 5 | 0.5 |
| Karstic dolomite, dolomite, chalky limestone | 5 | 0.3 |
| Limestone and dolostone, chalk | 5 | 0.5 |
| Reefal limestone, karstic limestone, dolomite, dolomite limestone | 5 | 0.3 |

# Groundwater Recharge – (R-Factor)

- When the geological formations that form the main aquifers are outcropping, the following Rainfall-Recharge equations were applied.

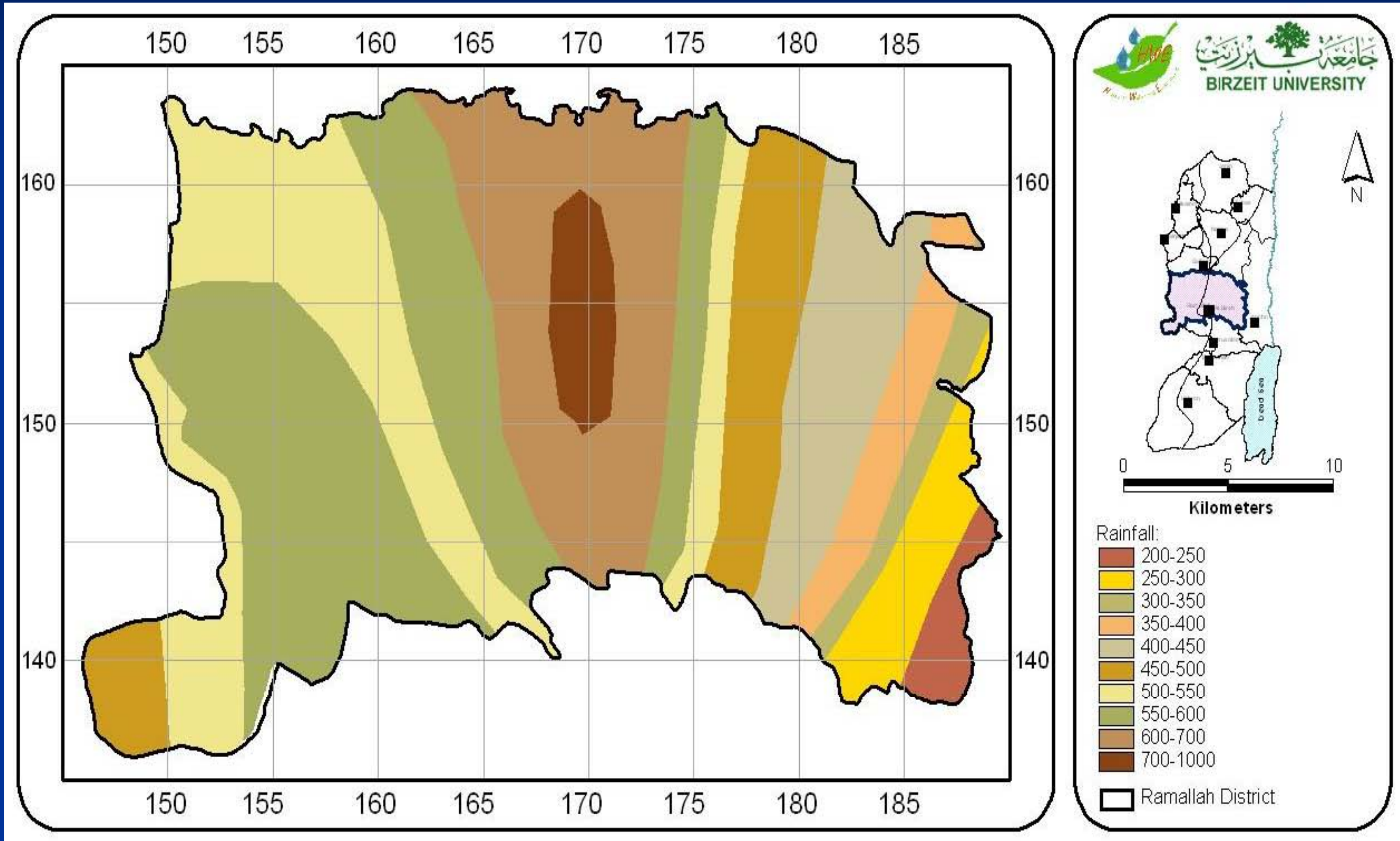
| | |
|---|---|
| $R = 0.6\,(P - 285)$ | $P > 700\ mm$ |
| $R = 0.46\,(P - 159)$ | $700\ mm > P > 456\ mm$ |
| $R = 0.3\,(P)$ | $456\ mm > P$ |

- where:

  R = Recharge from rainfall in mm/yr

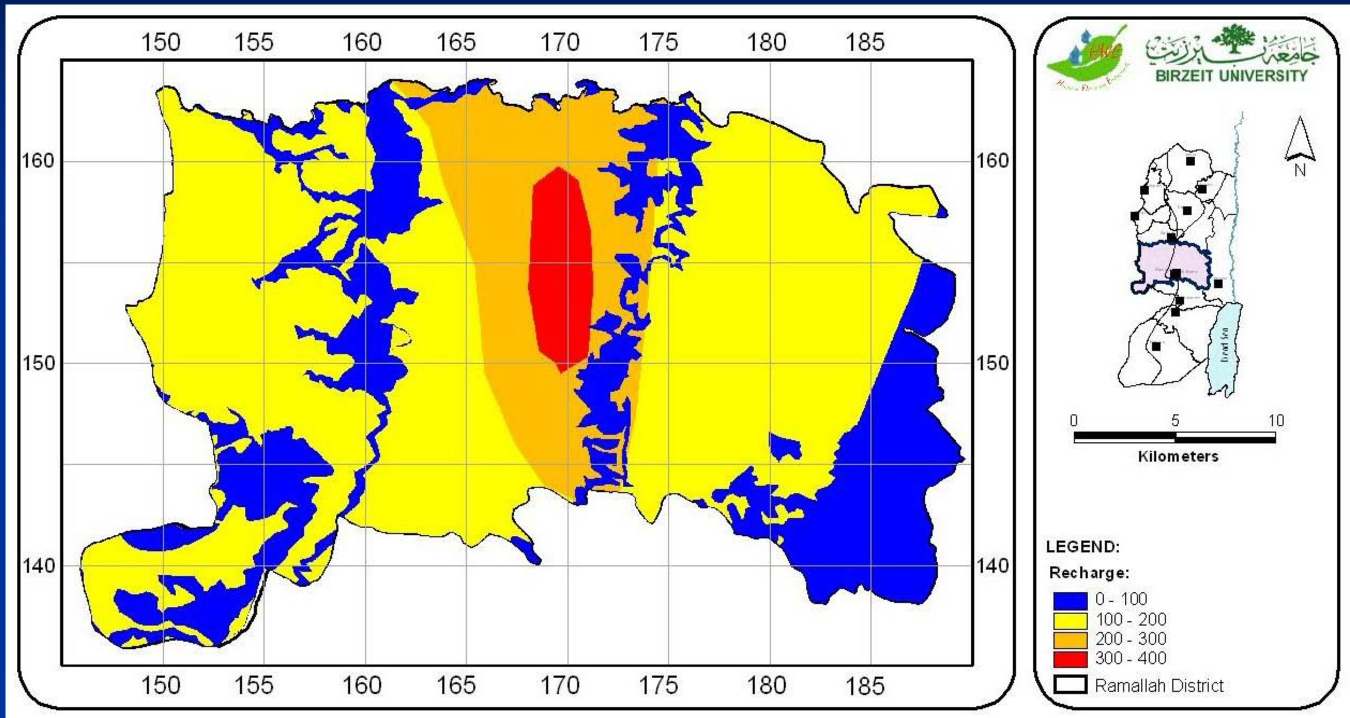
  P = Annual rainfall in mm/yr.

# Rainfall



150
155
160
165
170
175
180
185
160
150
140
BIRZEIT UNIVERSITY
N
0
5
10
Kilometers
Rainfall:
200-250
250-300
300-350
350-400
400-450
450-500
500-550
550-600
600-700
700-1000
Ramallah District

# Groundwater Recharge – (R-Factor)




| Mean annual rainfall (mm) | Recharge (mm/yr) | R value |
|---|---|---|
| 200 – 250 | 60 – 75 | 1.75 |
| 250 – 300 | 75 – 90 | 1.75 |
| 300 - 350 | 90 – 100 | 1.75 |
| 350 – 400 | 105 – 120 | 1.5 |
| 400 – 450 | 120 – 135 | 1.5 |
| 450-500 | 135 – 157 | 1.5 |
| 500-550 | 157 – 180 | 1.5 |
| 550-600 | 180 – 200 | 1.5 |
| 600-700 | 200 – 250 | 1.25 |
| 700-1000 | 250 - 430 | 1.00 |

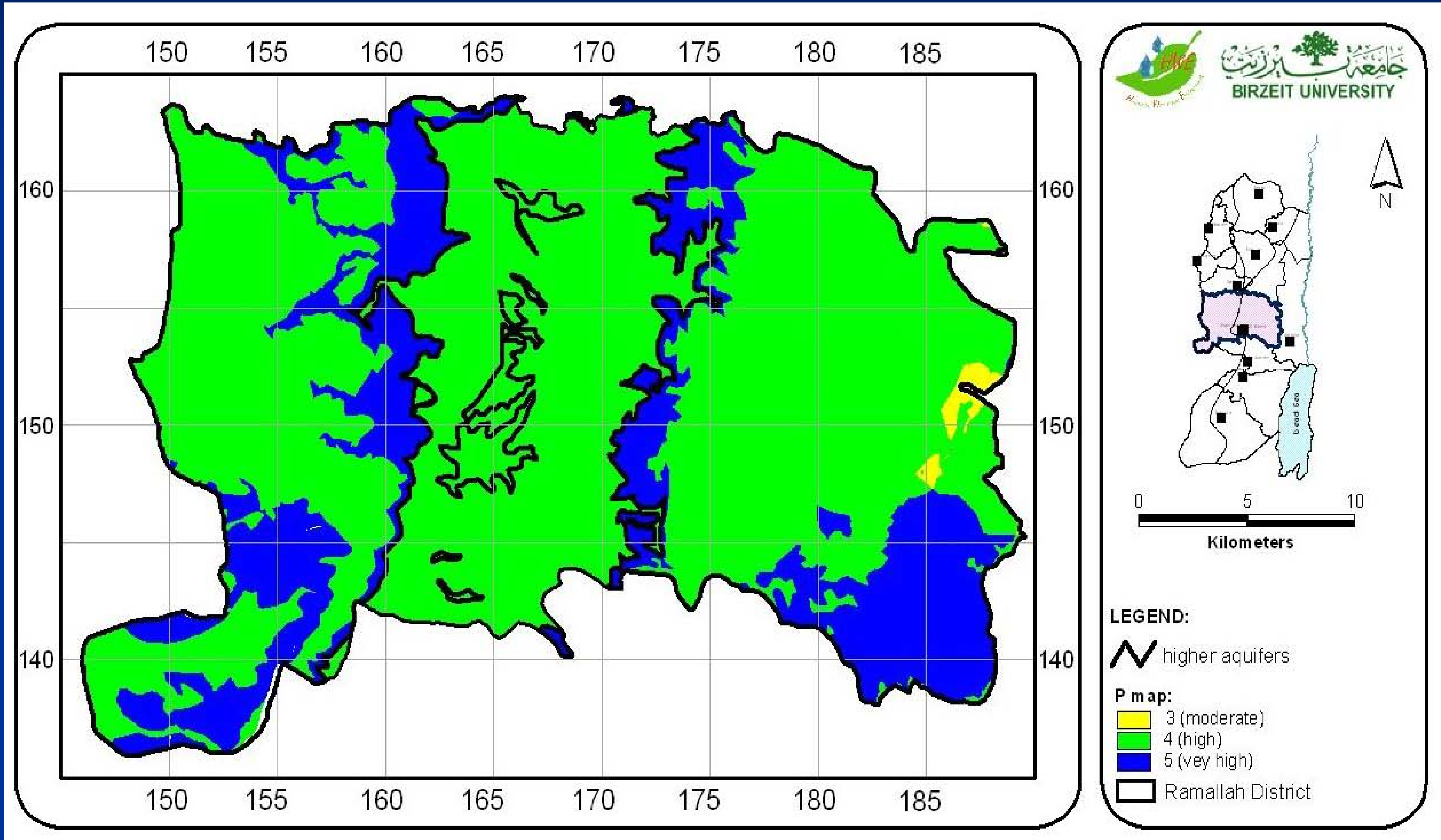
# P-Map

- Finally, P-map was prepared based on COST 620 mathematical equations as shown below.

$$P_{TS} = \left[ T + S.M + \left( \sum_{i=1}^{n} B_i \times M_i \right) \right] \times R + A$$

- The value $P_{TS}$ was calculated for each cell by using the previous described parameters maps, Hence, P-map is grid map with cell size (20m X 20m) where each has its own $P_{TS}$. According to the adapted P classification, It was found that about 5 $km^2$ (0.6% of total area) is classified as moderate protective, and 637 $km^2$ (76.7% of total area) is high protective whereas 189 $km^2$ (22.7% of total area) is very high protective areas.

# P-Map



150
155
160
165
170
175
180
185
160
150
140
BIRZEIT UNIVERSITY
N
0
5
10
Kilometers
LEGEND:
higher aquifers
P map:
3 (moderate)
4 (high)
5 (vey high)
Ramallah District

# I-Map

**1st Step: Determination of the dominant flow process**

| Saturated hydraulic conductivity [m/s] | Depth to low permeability layer: < 30 cm | 30-100 cm | > 100 cm |
|---|---|---|---|
| $> 10^{-4}$ | Type D | Type C | Type A |
| $> 10^{-5}-10^{-4}$ | | Type B | |
| $> 10^{-6}-10^{-5}$ | Type E | | |
| $< 10^{-6}$ | Type F | | |

**2nd Step: Determination of the I'-factor**

**Forest**

| dominant flow process | | Slope < 3.5 % | 3.5 - 27 % | > 27 % |
|---|---|---|---|---|
| infiltration | Type A | **1.0** | **1.0** | **1.0** |
| subsurface flow | Type B | 1.0 | 0.8 | 0.6 |
| | Type C | **1.0** | **0.6** | **0.6** |
| surface flow | Type D | 0.8 | 0.6 | 0.4 |
| | Type E | 1.0 | 0.6 | 0.4 |
| | Type F | **0.8** | **0.4** | **0.2** |

**Field/Meadow/Pature**

| dominant flow process | | Slope < 3.5 % | 3.5 - 27 % | > 27 % |
|---|---|---|---|---|
| infiltration | Type A | **1.0** | **1.0** | **0.8** |
| subsurface flow | Type B | 1.0 | 0.6 | 0.4 |
| | Type C | **1.0** | **0.4** | **0.2** |
| surface flow | Type D | 0.6 | 0.4 | 0.2 |
| | Type E | 0.8 | 0.4 | 0.2 |
| | Type F | **0.6** | **0.2** | **0.0** |

**3d Step: Determination of the I-factor**

| | Surface Catchment Map | I' factor: 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
|---|---|---|---|---|---|---|---|
| a | swallow hole, sinking stream and 10 m buffer | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| b | 100 m buffer on both sides of sinking stream | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
| c | catchment of sinking stream | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.0 |
| d | area discharging inside karst area | 0.4 | 0.6 | 0.8 | 1.0 | 1.0 | 1.0 |
| e | area discharging out of the karst area | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

↓

**I-map**

# Determination of Dominant Flow

- The dominant flow process is assessed on the basis of the top soil permeability and the presence of low permeable layers.

**1st Step: Determination of the dominant flow process**

| Saturated hydraulic conductivity [m/s] | Depth to low permeability layer < 30 cm | 30-100 cm | > 100 cm |
|---|---|---|---|
| $> 10^{-4}$ | Type D | Type C | Type A |
| $> 10^{-5}$-$10^{-4}$ | | Type B | |
| $> 10^{-6}$-$10^{-5}$ | | Type E | |
| $< 10^{-6}$ | | Type F | |

# Determination of Dominant Flow

- The dominant flow process is assessed on the basis of the top soil permeability and the presence of low permeable layers.

- Type A - Infiltration and subsequent percolation.

  Type B – Fast subsurface storm flow.

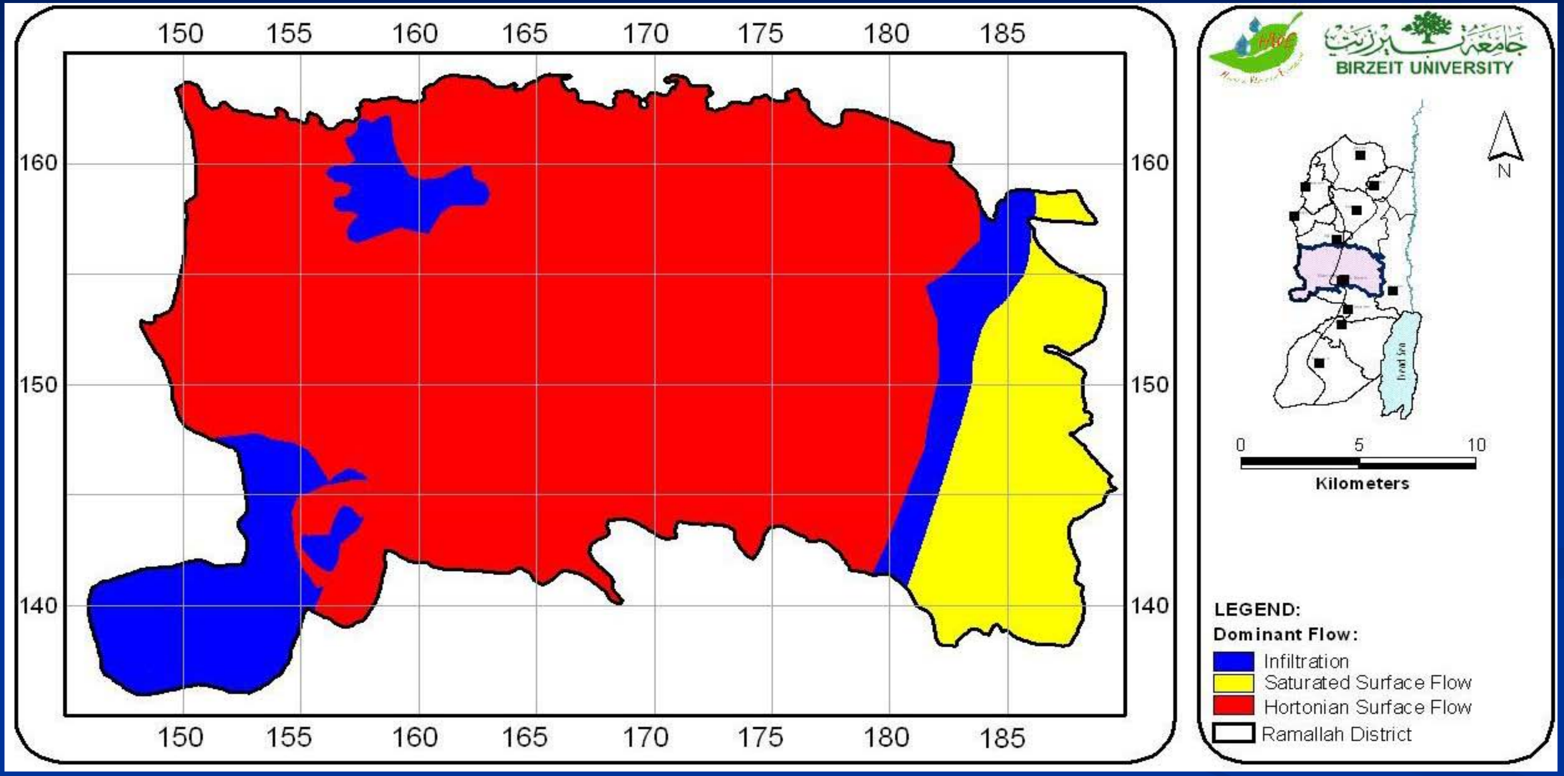
  Type C – Very fast subsurface flow.

  Type D – Saturated surface flow.

  Type E – Hortonian surface flow rarely (only during storm rainfall).

  Type F – Hortonian surface flow frequently (also during low intensive precipitation).

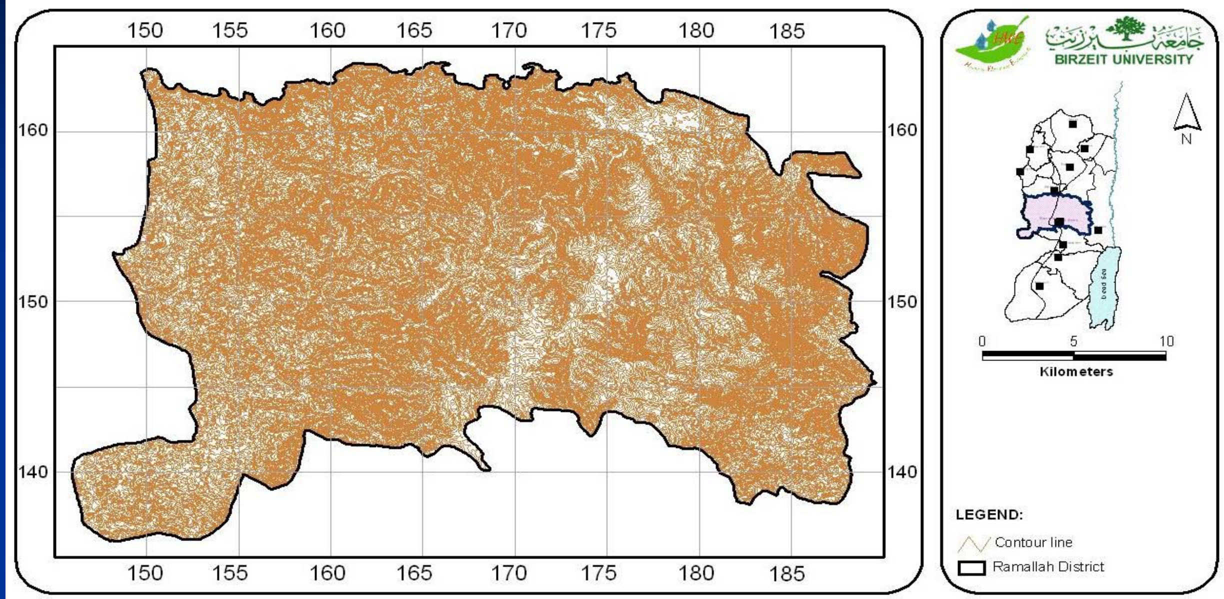
# Determination of Dominant Flow

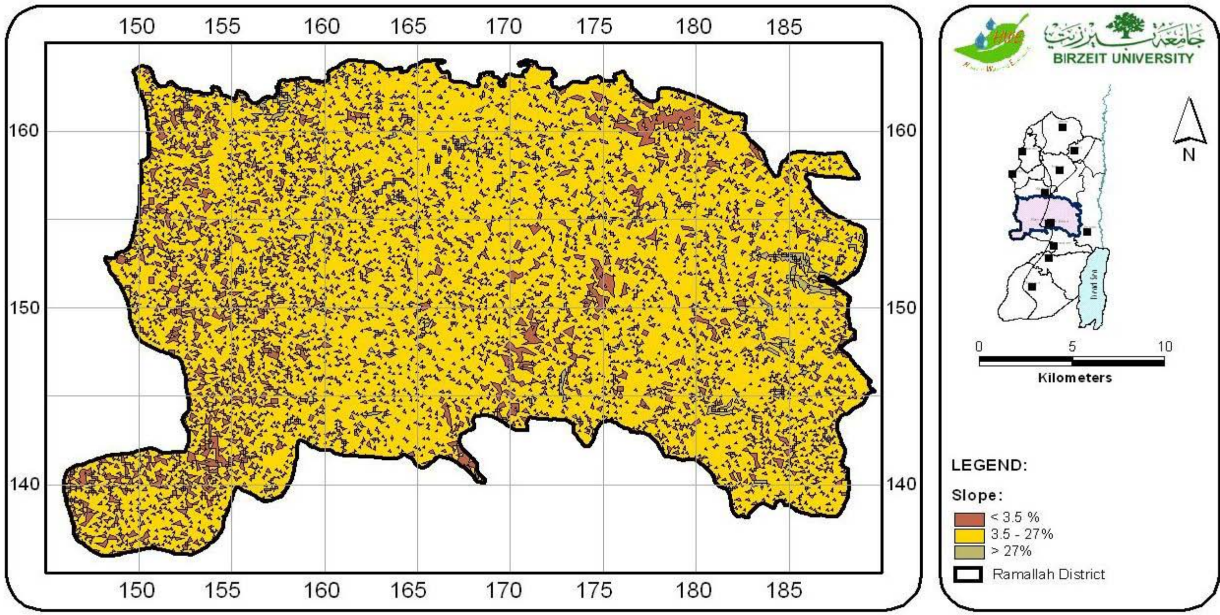



| Soil Type | Dominant Flow | Flow Type |
|---|---|---|
| Terra Rossa, Brown Rendzinas and Pale Rendzinas | Hortonian Surface Flow | F |
| Brown Rendzinas and Pale Rendzinas | Infiltration and Subsequent Percolations | A |
| Grumusols | Hortonian Surface Flow | F |
| Brown Lithosols and Loessial Serozems | Saturated Surface Flow | D |
| Brown Lithosols and Loessial Arid Brown Soil | Saturated Surface Flow | D |
| Loessial Serozems | Saturated Surface Flow | D |

# Determination of Slope

## Contour Map




## Slope Map

# Determination of I' Factor

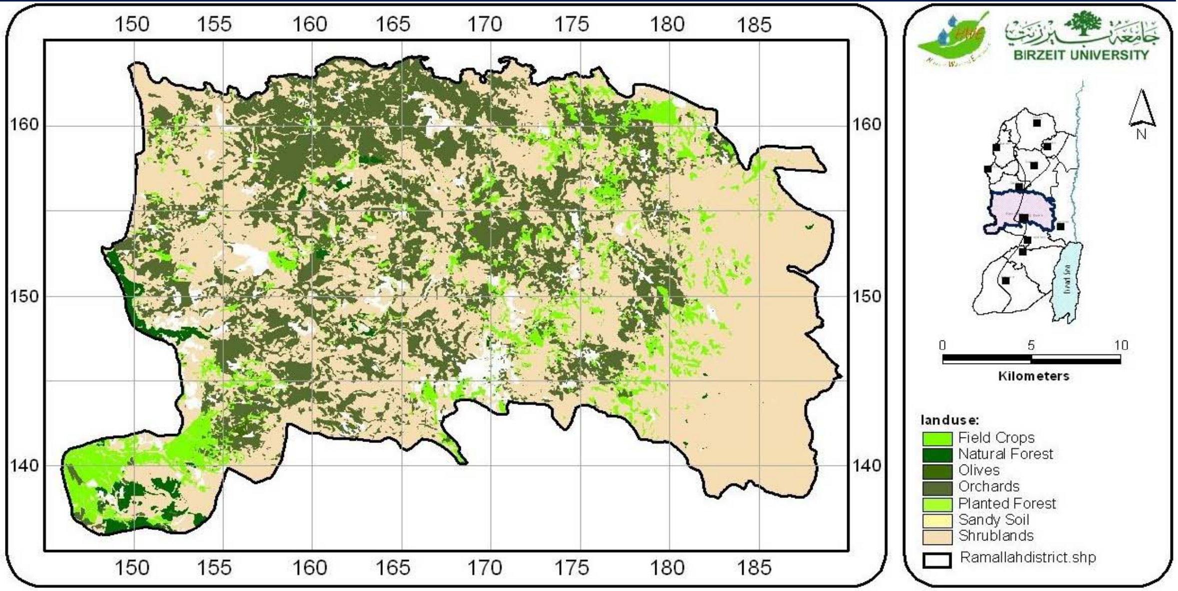
**2nd Step: Determination of the I'-factor**

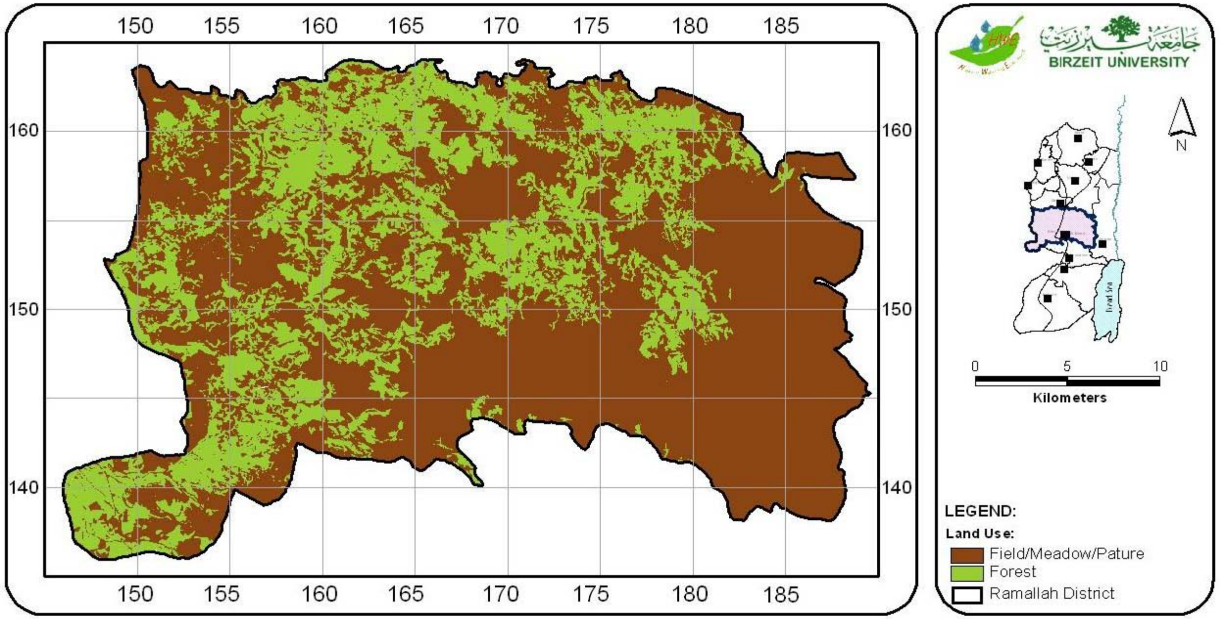
| Forest | | | | |
|---|---|---|---|---|
| dominant flow process | | Slope < 3.5 % | Slope 3.5 - 27 % | Slope > 27 % |
| infiltration | Type A | **1.0** | **1.0** | **1.0** |
| subsurface flow | Type B | 1.0 | 0.8 | 0.6 |
| | Type C | **1.0** | **0.6** | **0.6** |
| surface flow | Type D | 0.8 | 0.6 | 0.4 |
| | Type E | 1.0 | 0.6 | 0.4 |
| | Type F | **0.8** | **0.4** | **0.2** |

| Field/Meadow/Pature | | | | |
|---|---|---|---|---|
| dominant flow process | | Slope < 3.5 % | Slope 3.5 - 27 % | Slope > 27 % |
| infiltration | Type A | **1.0** | **1.0** | **0.8** |
| subsurface flow | Type B | 1.0 | 0.6 | 0.4 |
| | Type C | **1.0** | **0.4** | **0.2** |
| surface flow | Type D | 0.6 | 0.4 | 0.2 |
| | Type E | 0.8 | 0.4 | 0.2 |
| | Type F | **0.6** | **0.2** | **0.0** |

# LandUse Map

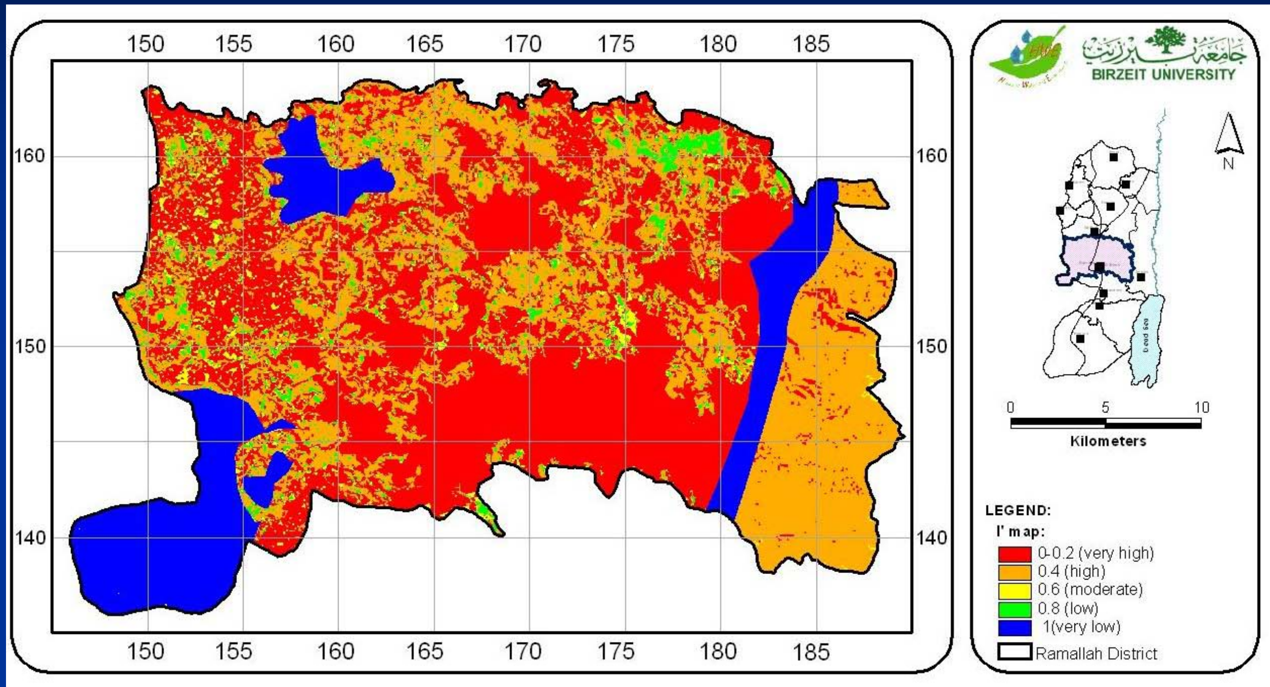
LandUse Map




PI- LU Map

# I’ Map



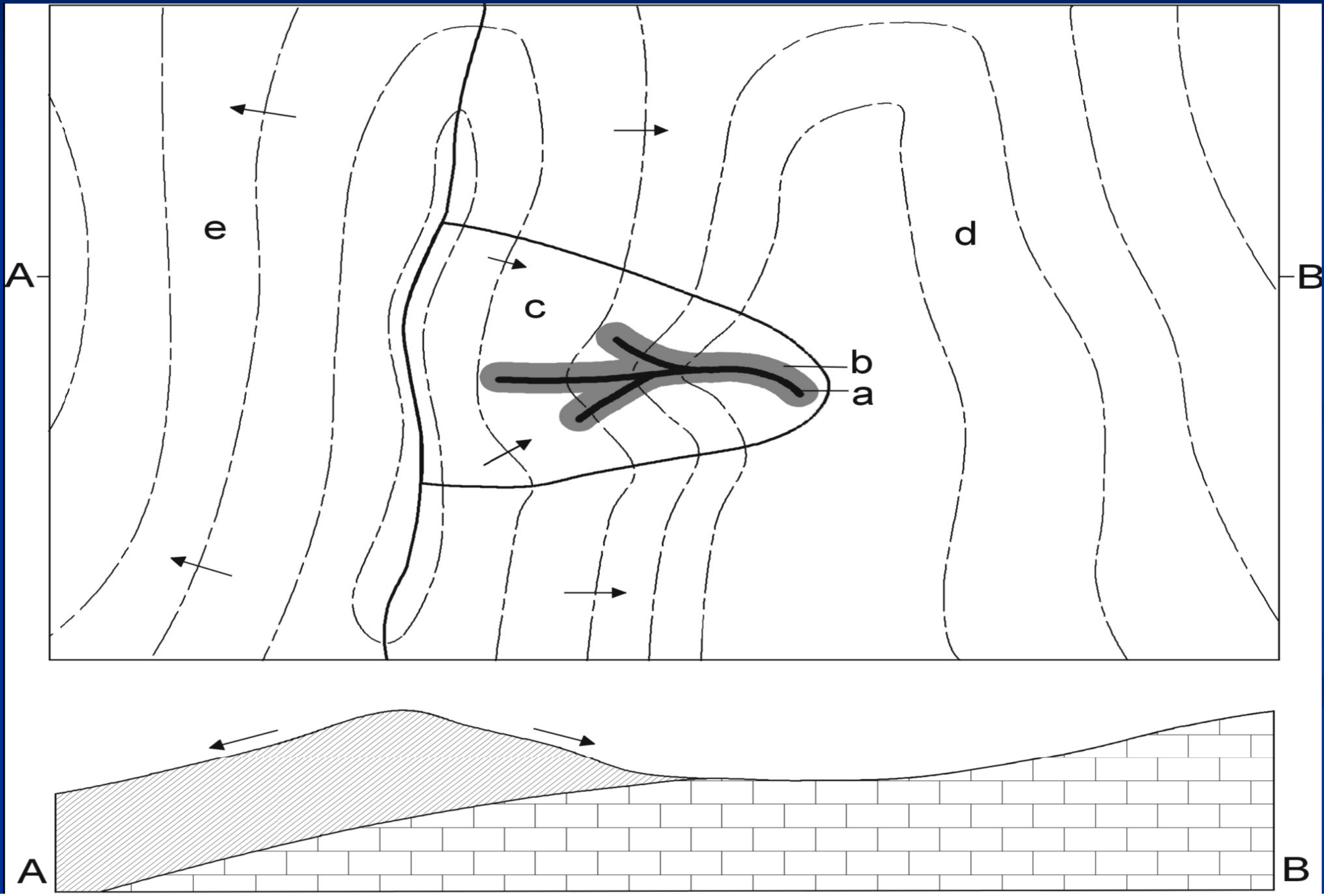

**Forests**

| Dominant Flow Type | Slope | | |
|---|---|---|---|
| | **0 – 3.5 %** | **3.5 – 27 %** | **> 27 %** |
| Type A | 1.0 | 1.0 | 1.0 |
| Type D | 0.8 | 0.6 | 0.4 |
| Type F | 0.8 | 0.4 | 0.2 |

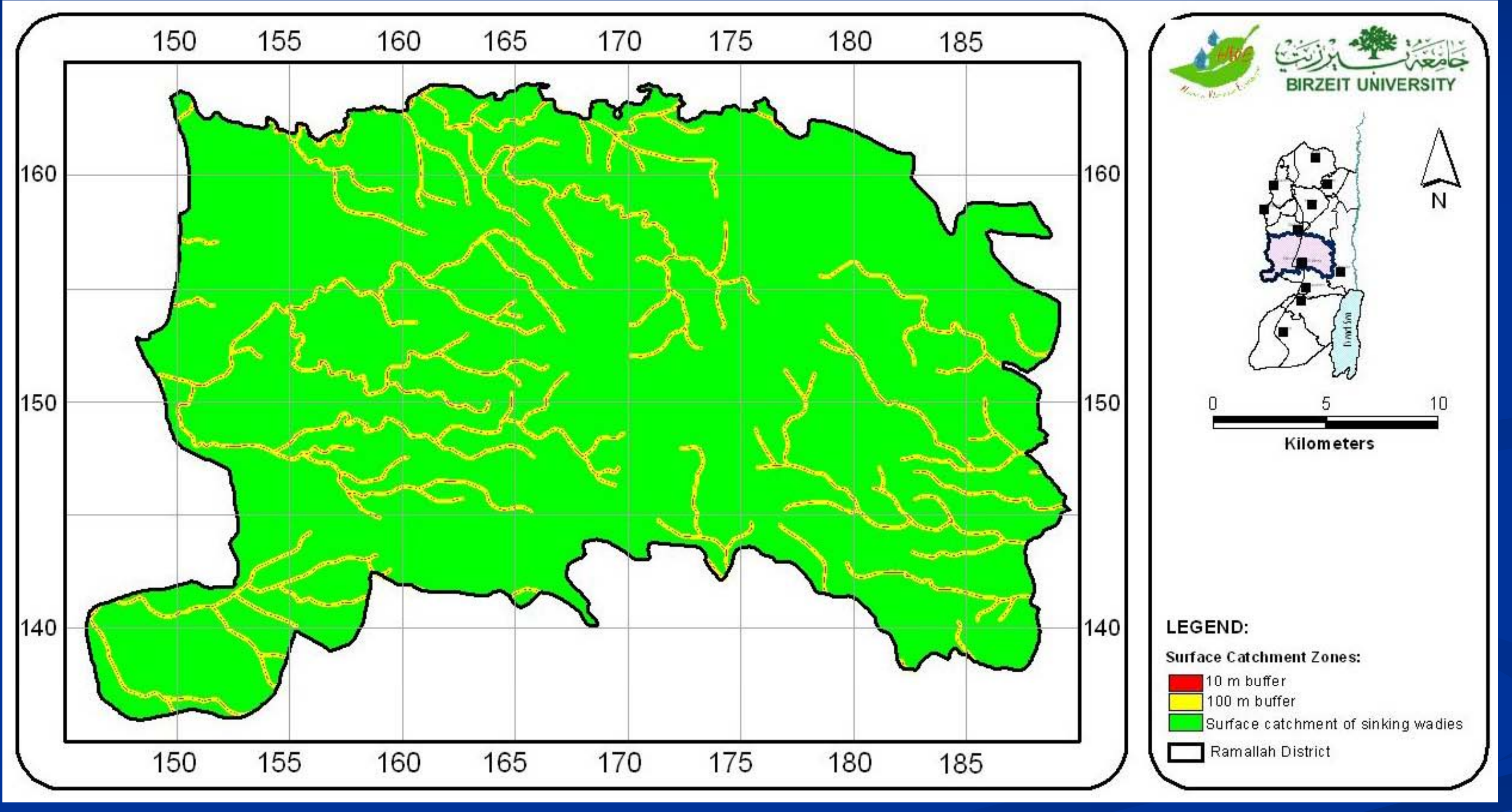
**Fields**

| Dominant Flow Type | Slope | | |
|---|---|---|---|
| | **0 – 3.5 %** | **3.5 – 27 %** | **> 27 %** |
| Type A | 1.0 | 1.0 | 1.0 |
| Type D | 0.6 | 0.4 | 0.2 |
| Type F | 0.6 | 0.2 | 0.0 |

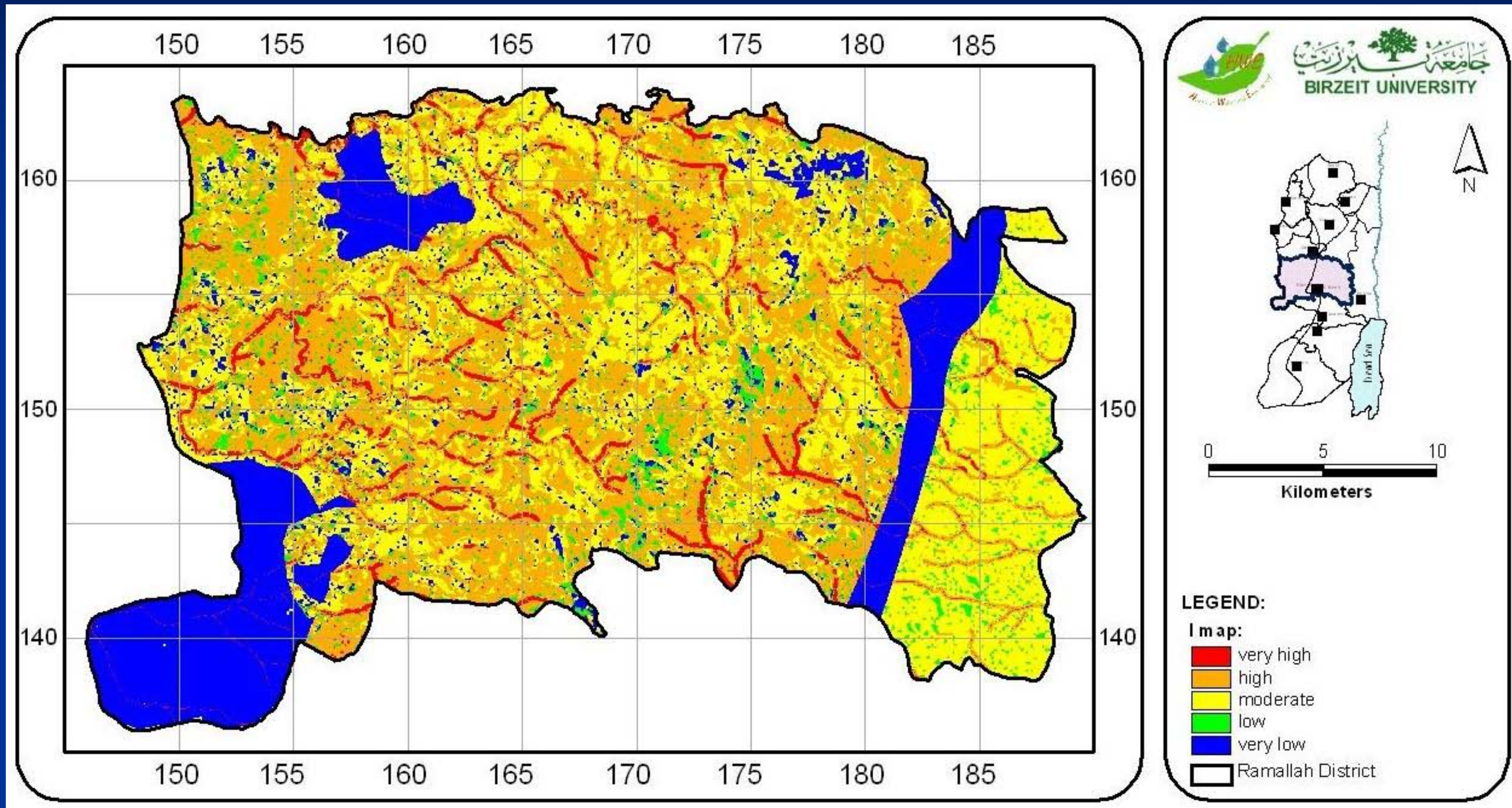
# Surface Catchment Map



# Surface Catchment Map



# I-Map




| Surface Catchment Map | | I' Factor | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
| a | 10 m buffer on both sides of sinking wadis | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| b | 100 m buffer on both sides of sinking wadis | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
| c | Catchment of sinking wadis | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.0 |

# Determination of Dominant Flow

- The dominant flow process is assessed on the basis of the top soil permeability and the presence of low permeable layers.

- Type A - Infiltration and subsequent percolation.
  Type B – Fast subsurface storm flow.
  Type C – Very fast subsurface flow.
  Type D – Saturated surface flow.
  Type E – Hortonian surface flow rarely (only during storm rainfall).
  Type F – Hortonian surface flow frequently (also during low intensive precipitation).

# PI - Map

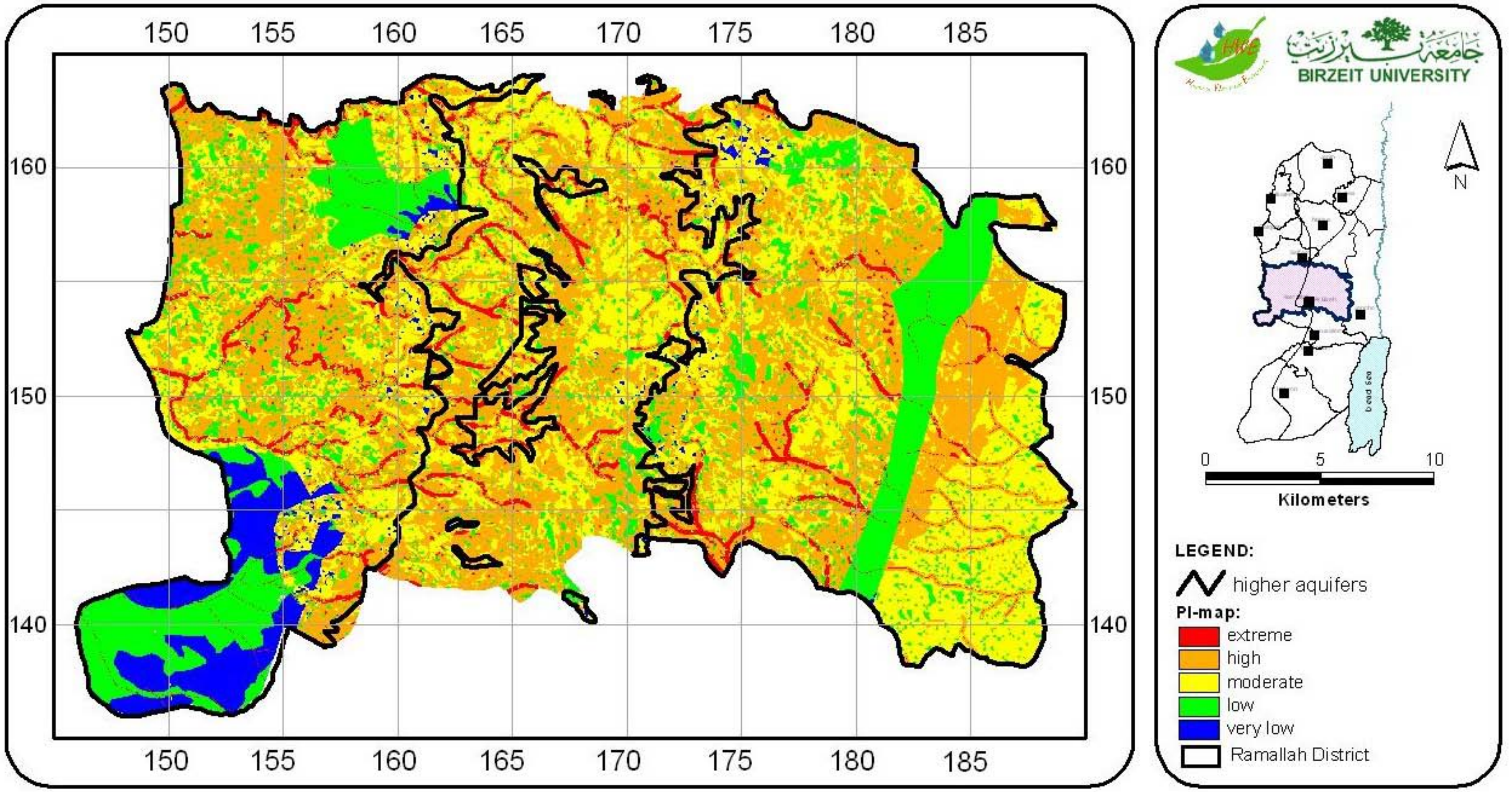
- The vulnerability map shows the intrinsic vulnerability and the natural protection of the uppermost aquifer. The map shows the spatial distribution of the protection factor π, which is obtained by multiplying the P and I factors:

$$\pi = P \cdot I$$

- The areas on each of the three maps are assigned to one of five classes, symbolized by five colors: from red for high risk to blue for low risk. Consequently, one legend can be used for all three maps.

# PI - Map

| Color | Vulnerability Map (Vulnerability of GW) | | P- Map (Protection Cover) | | I – Map (Degree of Bypassing) | |
|---|---|---|---|---|---|---|
| | Description | π- factor | Description | P – factor | Description | I – factor |
| Red | Extreme | 0-1 | Very low | 1 | Very high | 0.0 – 0.2 |
| Orange | High | > 1-2 | Low | 2 | High | 0.4 |
| Yellow | Moderate | >2-3 | Moderate | 3 | Moderate | 0.6 |
| Green | Low | >3-4 | High | 4 | Low | 0.8 |
| Blue | Very low | >4-5 | Very high | 5 | Very low | 1.0 |



# PI - Map

- From the final PI-map, 5% of the study area (41.6 $km^2$) is classified as extreme, 41% (340.7 $km^2$) as high, 31% (257.6 $km^2$) as moderate, 18% (149.6 $km^2$) as low and 5% (41.6 $km^2$) as very low. Hence, Ramallah-Al Bireh district is classified as high-to-moderate vulnerable.

**THANK YOU**