MEDFRIEND2012
INTERNATIONAL CONFERENCE SEDIMENT TRANSPORT MODELLING IN HYDROLOGICAL WATERSHEDS AND RIVERS
ISTANBUL, TURKEY, 14-16 NOVEMBER, 2012

# THE EFFECT OF RESERVOIR SEDIMENTATION ON COASTAL EROSION: THE CASE OF NESTOS RIVER, GREECE

M. ANDREDAKI, A. GEORGOULAS, V. HRISSANTHOU AND N. KOTSOVINOS

DEPARTMENT OF CIVIL ENGINEERING
DEMOCRITUS UNIVERSITY OF THRACE
67100 XANTHI, GREECE

# INTRODUCTION

- Nestos River flows through two European countries, Bulgaria and Greece, and discharges its water into the Aegean Sea
- Nestos River basin: 5100 km$^2$
- Two dams in the Greek part of Nestos River:
  Thisavros Dam and Platanovrysi Dam
- Reduction of sediment yield at the outlet of Nestos River basin
- Coastal erosion

# INTRODUCTION

- Calculation of sediment yield before and after the dams construction:
  Mathematical simulation modeling

- Estimate of coastal erosion:
  Remote sensing techniques (satellite images, aerial photographs)
  Field surveying (DGPS)

# MATHEMATICAL MODEL

<u>Three submodels</u>:

- Hydrological submodel
- Soil erosion submodel (Schmidt, 1992)
- Stream sediment transport submodel (Yang and Stall, 1976)

- The calculations were performed on a monthly time basis

- Final result: Mean annual value of sediment yield

# HYDROLOGICAL SUBMODEL

<u>Simplified water balance model for the root zone of the soil</u>:

$$S_n' = S_{n-1} + N_n - E_{pn}$$

S: available soil moisture [mm]

N: rainfall amount [mm]

$E_p$: potential evapotranspiration [mm]

n: index for the time step

# HYDROLOGICAL SUBMODEL

If $S_n' < 0$, then $S_n = 0$, $h_{on} = 0$, $IN_n = 0$

If $0 \leq S_n' \leq S_{max}$, then $S_n = S_n'$, $h_{on} = 0$, $IN_n = 0$

If $S_n' > S_{max}$, then $S_n = S_{max}$, $h_{on} = K(S_n' - S_{max})$, $IN_n = K'(S_n' - S_{max})$
where $K' = 1 - K$

$h_o$: direct runoff [mm]
IN: deep percolation [mm]
$S_{max}$: maximum available soil moisture [mm]
K, K′: proportionality coefficients

# SOIL EROSION SUBMODEL
## (Schmidt, 1992)

$$\varphi_r = C r \rho A u_r \sin\alpha$$

$\varphi_r$: momentum flux by the droplets [kg m/s²]

C: soil cover factor

r: rainfall intensity [m/s]

$\rho$: water density [kg/m³]

A: sub-basin area [m²]

$u_r$: mean fall velocity of the droplets [m/s]

$\alpha$: mean slope angle of the soil surface [°]

# SOIL EROSION SUBMODEL

$$\varphi_f = q\rho b u$$

$\varphi_f$: momentum flux by the runoff [kg m/s²]

q: direct runoff rate per unit width [m³/(s m)]

ρ: water density [kg/m³]

b: width of the sub-basin area [m]

u: mean flow velocity [m/s]

# SOIL EROSION SUBMODEL

$$q_{rf} = (1.7E-1.7)10^{-4} \qquad E = (\varphi_r+\varphi_f) / \varphi_{cr} \qquad (E>1)$$

$q_{rf}$: available sediment discharge per unit width [kg/(m s)]

$\varphi_r$: momentum flux by the droplets [kg m/s$^2$]

$\varphi_f$: momentum flux by the runoff [kg m/s$^2$]

$\varphi_{cr}$: critical momentum flux [kg m/s$^2$]

# SOIL EROSION SUBMODEL

$$q_t = c_{max}\rho_s q$$

$q_t$: sediment transport capacity by overland flow [kg/(m s)]

$c_{max}$: concentration of suspended particles at transport capacity [m³/m³]

$\rho_s$: sediment density [kg/m³]

$q$: direct runoff rate per unit width [m³/(s m)]

# SOIL EROSION SUBMODEL

**Estimation of sediment ES reaching the main stream from the respective sub-basin area**

$$\text{If } q_{rf} > q_t, \text{ then } ES = q_t$$
$$\text{If } q_{rf} < q_t, \text{ then } ES = q_{rf}$$

**$q_t$: sediment transport capacity by overland flow**

## STREAM SEDIMENT TRANSPORT SUBMODEL

**Estimation of sediment load FLO at the outlet of the main stream of a sub-basin**

**If ESI > $q_{ts}$, then FLO = $q_{ts}$**

**If ESI < $q_{ts}$, then FLO = ESI**

**ESI: available sediment load in the main stream considered**

**$q_{ts}$: sediment transport capacity by streamflow**

# STREAM SEDIMENT TRANSPORT SUBMODEL

$$\log c_t = 5.435 - 0.286\log(wD_{50}/v) - 0.457\log(u_*/w) +$$
$$+[1.799 - 0.409\log(wD_{50}/v) - 0.314\log(u_*/w)]\log(us/w - u_{cr}s/w)$$

(Yang and Stall, 1976)

$c_t$: total sediment concentration by weight [ppm]

$w$: terminal fall velocity of suspended particles [m/s]

$D_{50}$: median particle diameter of bed material [m]

$v$: kinematic viscosity of the water [$m^2$/s]

$u$: mean flow velocity [m/s]

$u_{cr}$: critical mean flow velocity [m/s]

$u_*$: shear velocity [m/s]

$s$: energy slope

# APPLICATION OF MATHEMATICAL MODEL TO NESTOS RIVER BASIN

Basin of Nestos River:

- Division into 60 sub-basins:

- Basin of Thisavros Dam (Bulgarian and Greek parts): 31 sub-basins
- Basin of Platanovrysi Dam (Greece): 9 sub-basins
- Basin downstream of Platanovrysi Dam: 20 sub-basins

- Meteorological data (rainfall and temperature): from 22 meteorological stations in Greece and Bulgaria

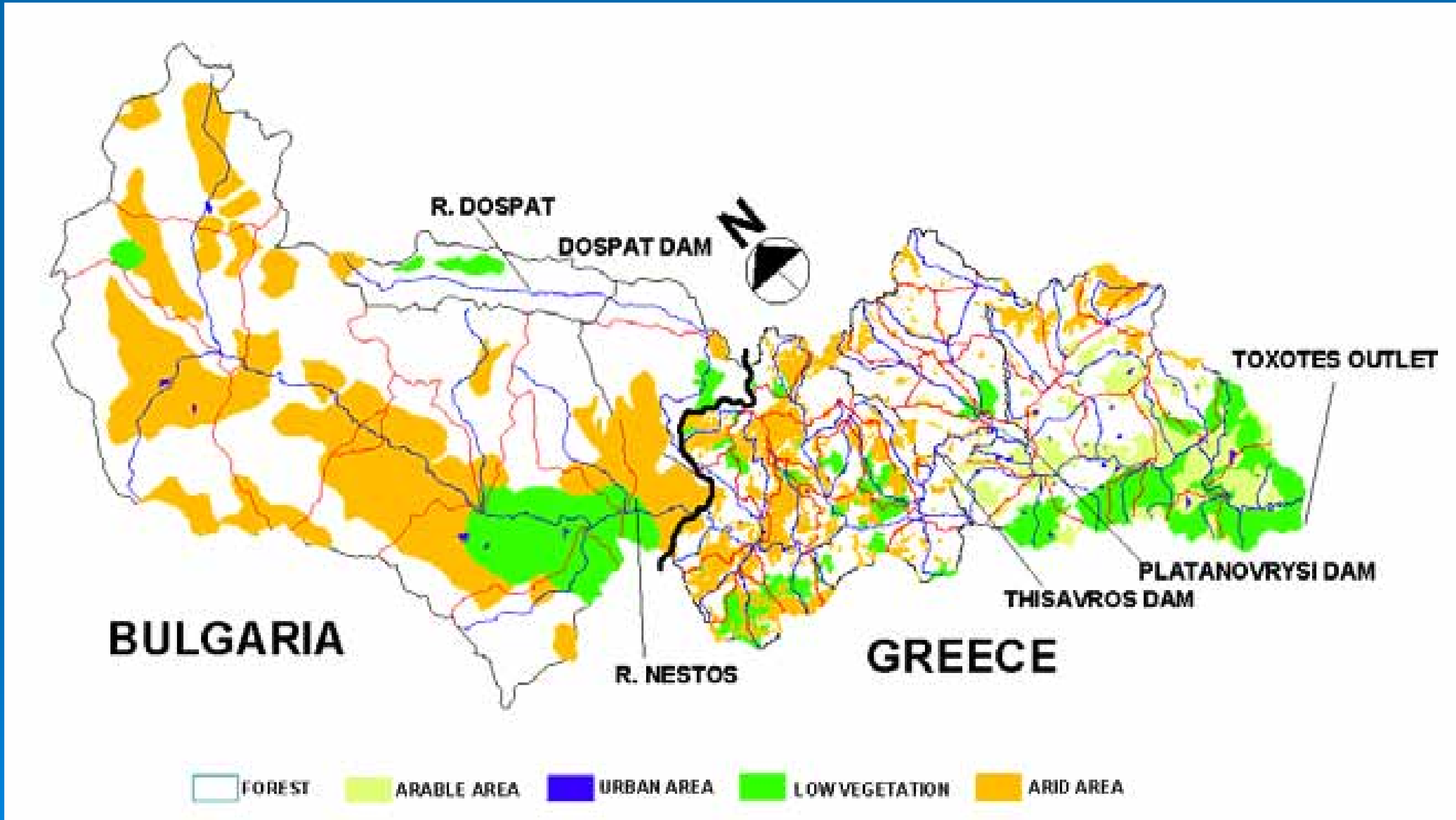
# APPLICATION OF MATHEMATICAL MODEL TO NESTOS RIVER BASIN

**Thematic maps:**

- **Altitude contours map**
- **Main streams map**
- **Soil cover map**
- **Geological map**
- **Thiessen polygons map**

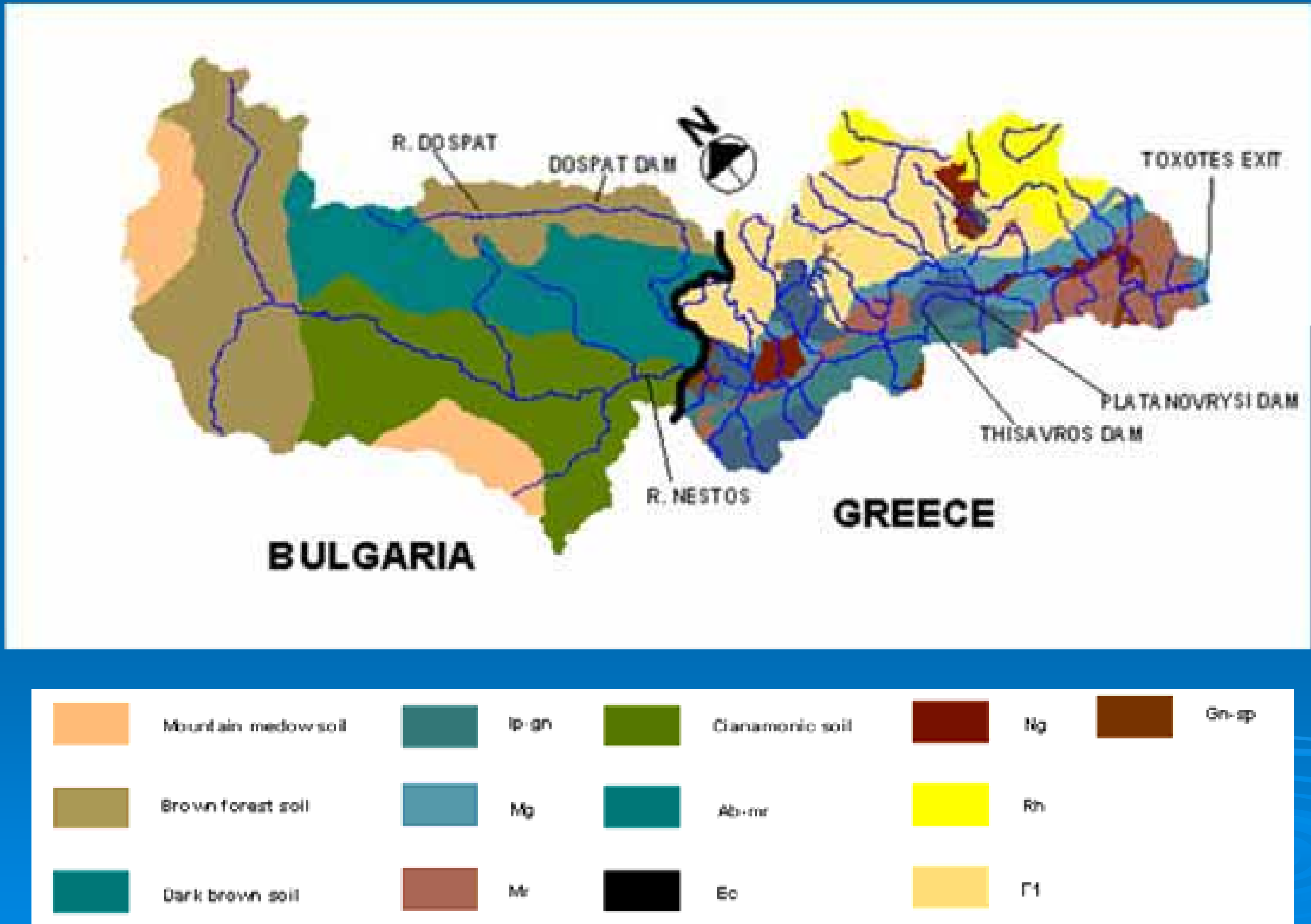
# APPLICATION OF MATHEMATICAL MODEL TO NESTOS RIVER BASIN

## Main streams and soil cover map



# APPLICATION OF MATHEMATICAL MODEL TO NESTOS RIVER BASIN

## Geological map

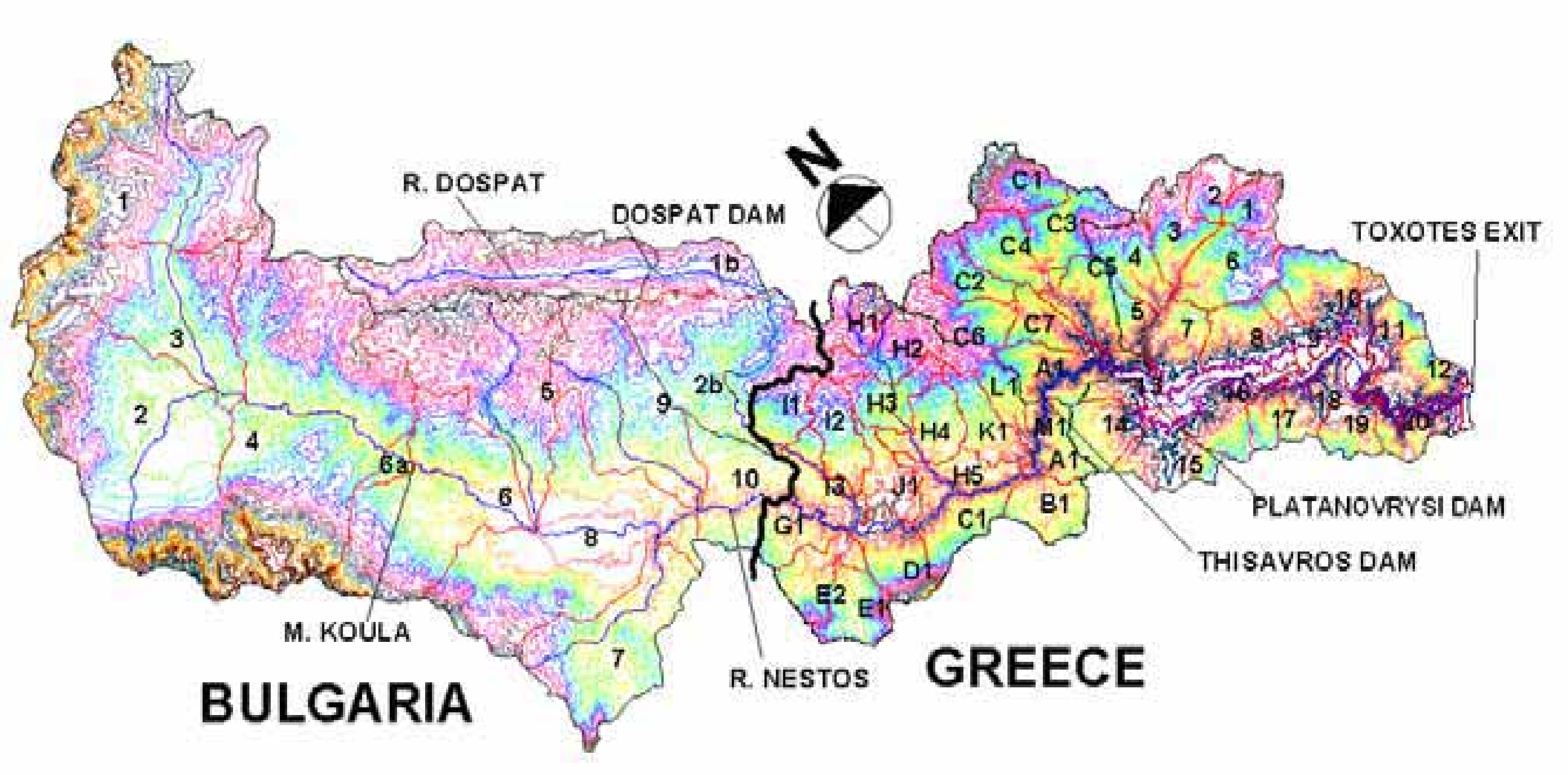


# APPLICATION OF MATHEMATICAL MODEL TO NESTOS RIVER BASIN

## Thiessen polygons map

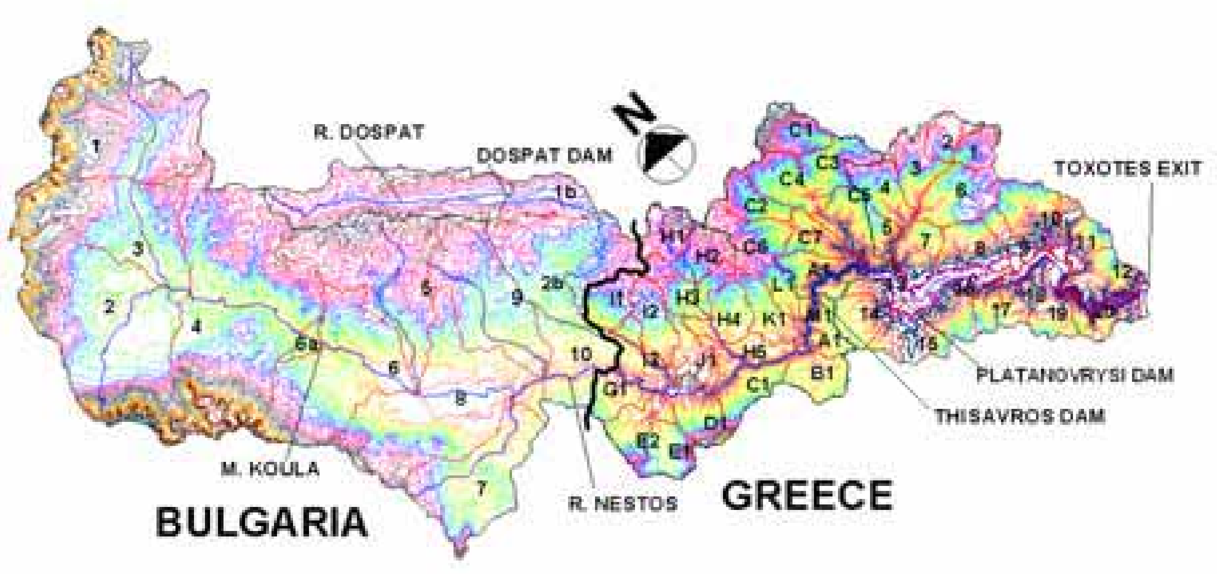
# APPLICATION OF MATHEMATICAL MODEL TO NESTOS RIVER BASIN

## Altitude contours map



# APPLICATION OF MATHEMATICAL MODEL TO NESTOS RIVER BASIN
## Model testing

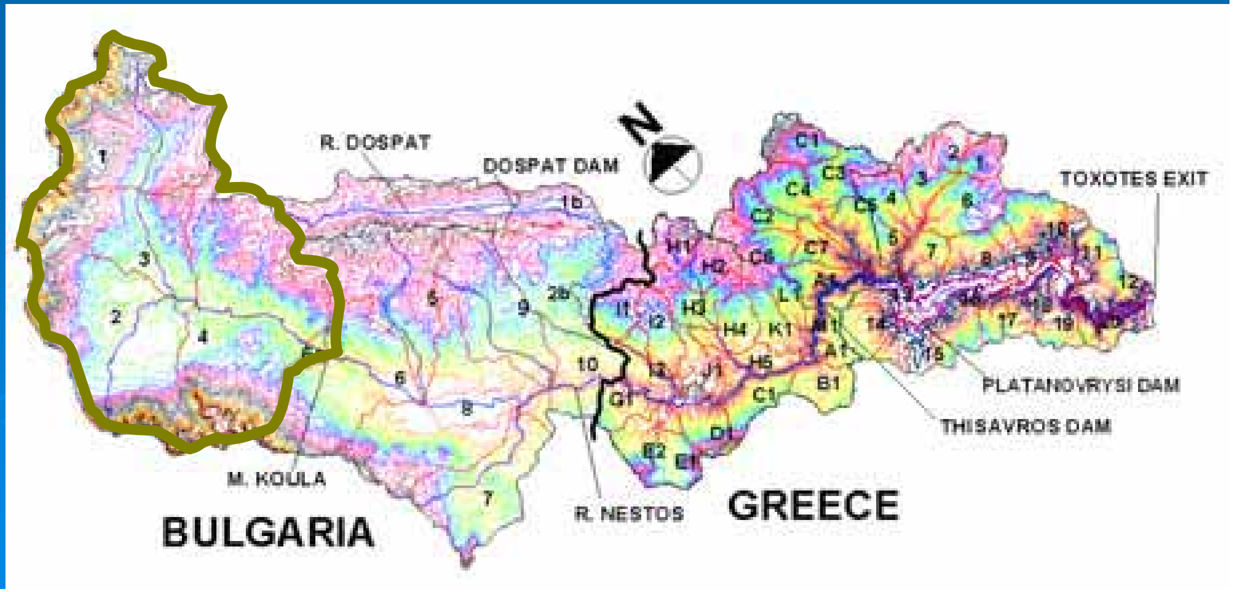
- Sediment (suspended load) measurements of 53 years (1937–1989) at the location "Momina Koula" (Bulgaria)
- Basin area: 1511 km²
- Mean annual suspended sediment yield: 202 t/km²
- Assumption: Bed load / Suspended load = 0.25
- Mean annual sediment yield (measured): 252.5 t/km²
- Mean annual sediment yield (computed): 208 t/km²
- Underestimation: 18%



# APPLICATION OF MATHEMATICAL MODEL TO NESTOS RIVER BASIN

## Model testing

- Sediment (suspended load) measurements of 53 years (1937–1989) at the location "Momina Koula" (Bulgaria)
- Basin area: 1511 km²
- Mean annual suspended sediment yield: 202 t/km²
- Assumption: Bed load / Suspended load = 0.25
- Mean annual sediment yield (measured): 252.5 t/km²
- Mean annual sediment yield (computed): 208 t/km²
- Underestimation: 18%



# APPLICATION OF MATHEMATICAL MODEL TO NESTOS RIVER BASIN

## Calculations

- Time period of 11 years (1980-1990)
- Mean annual sediment amount inflowing into Thisavros Reservoir:

  from the Bulgarian part (3052 km²) and from the Greek part (804 km²) of Nestos River basin.
- Mean annual sediment amount inflowing into Platanovrysi Reservoir from the corresponding basin (405 km², Greece)
- Mean annual sediment yield at the outlet of Nestos River basin (Toxotes) originating from the basin part downstream of Platanovrysi Dam (840 km², Greece)

# COMPUTATIONAL RESULTS

- Mean annual sediment yield at the outlet of Nestos River basin, before the dams construction: $2x10^6$ t
- Mean annual sediment yield at the outlet of Nestos River basin, after the dams construction: $0.33x10^6$ t
- Decrease of sediment yield due to the dams construction: 84%
- Consequence: Erosion of Nestos River mouth and the neighbouring coastline

# SHORELINE CHANGE MONITORING
## Adopted Methodology

- **Shoreline in the year 2002**

  *- Use of ortho-rectified/geo-referenced, satellite images that were available in the QB archive*

- **Shoreline in the year 2007**

  *- Use of high resolution DGPS (Differential Global Positioning System) field measurements*

- **Comparison of the extracted shorelines between the years *2002* and *2007* in order to access a *short term shoreline evolution* of the region that roughly corresponds to the *period after the construction of the dams*.**

# SHORELINE CHANGE MONITORING
## Adopted Methodology

- **Shoreline in the year 1945**

  *- Ortho-rectification/geo-referencing of available, old aerial photographs of the region from the HMGS and extraction of an old shoreline.*

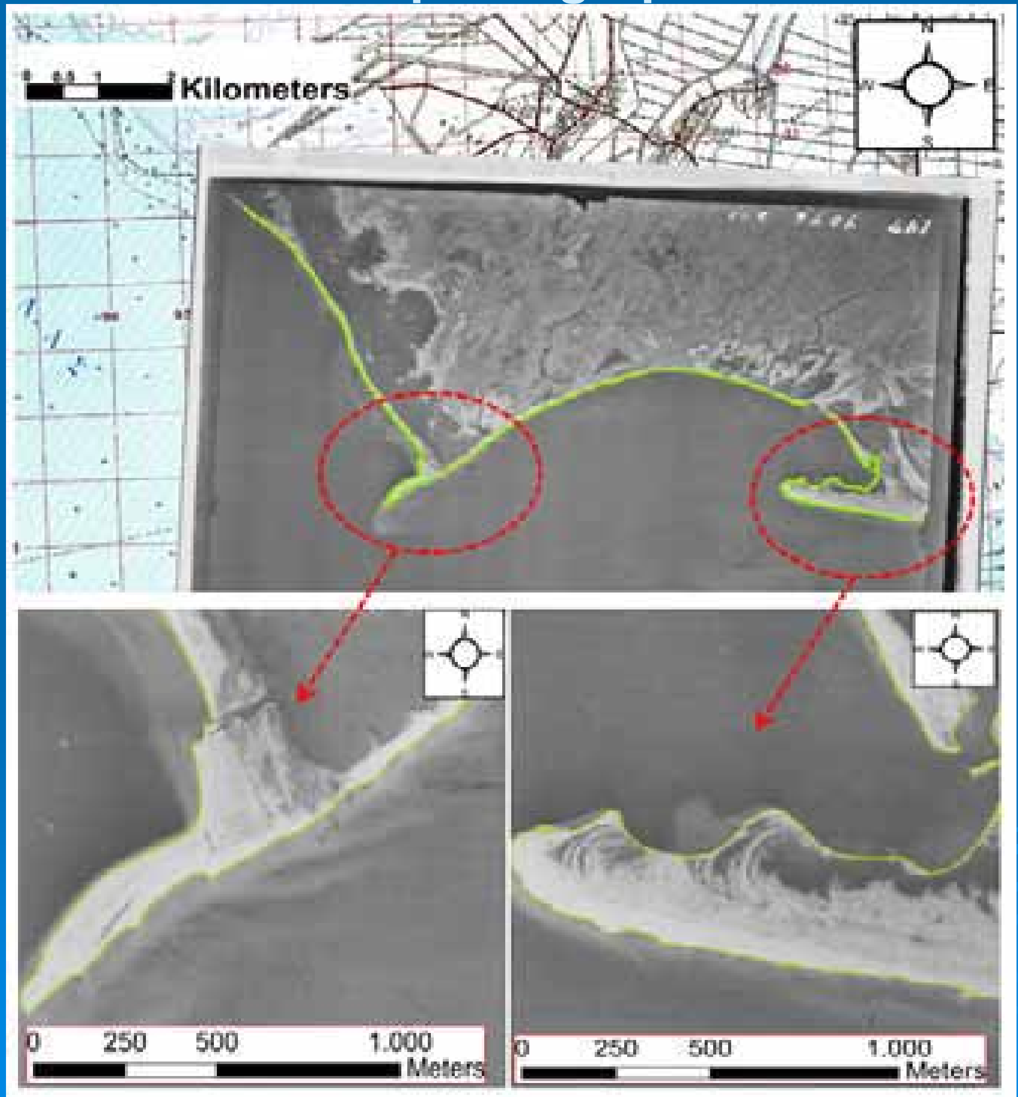
- **Comparison of the extracted shorelines between the years *1945* and *2002* in order to access a *long term shoreline evolution* of the region that roughly corresponds to *the period before the construction of the dams*.**

# SHORELINE CHANGE MONITORING

## Pilot study region for shoreline change monitoring and selected region for testing the accuracy and effectiveness of the adopted shoreline change monitoring methodology

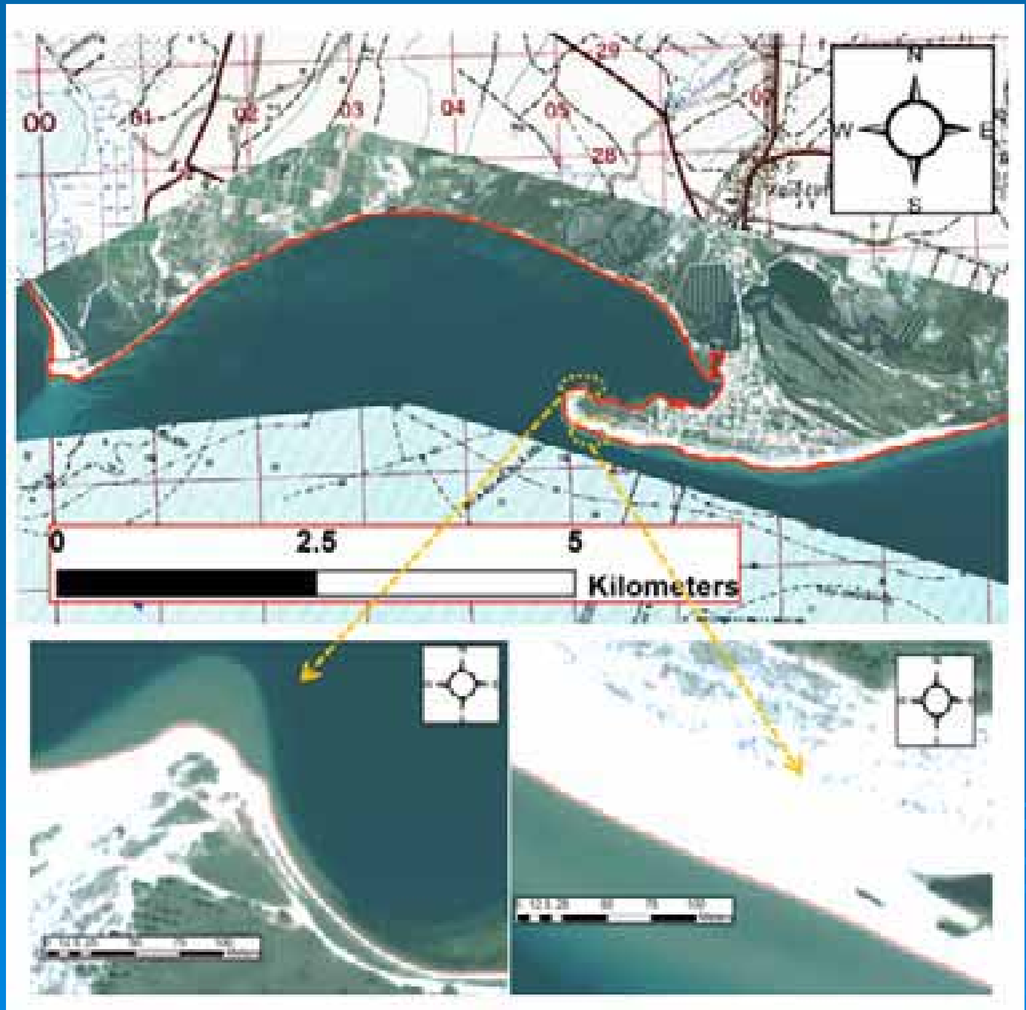
# SHORELINE CHANGE MONITORING

## Digitally extracted shoreline from the aerial photograph that corresponds to the test region (year 1945), superimposed on the aerial photograph



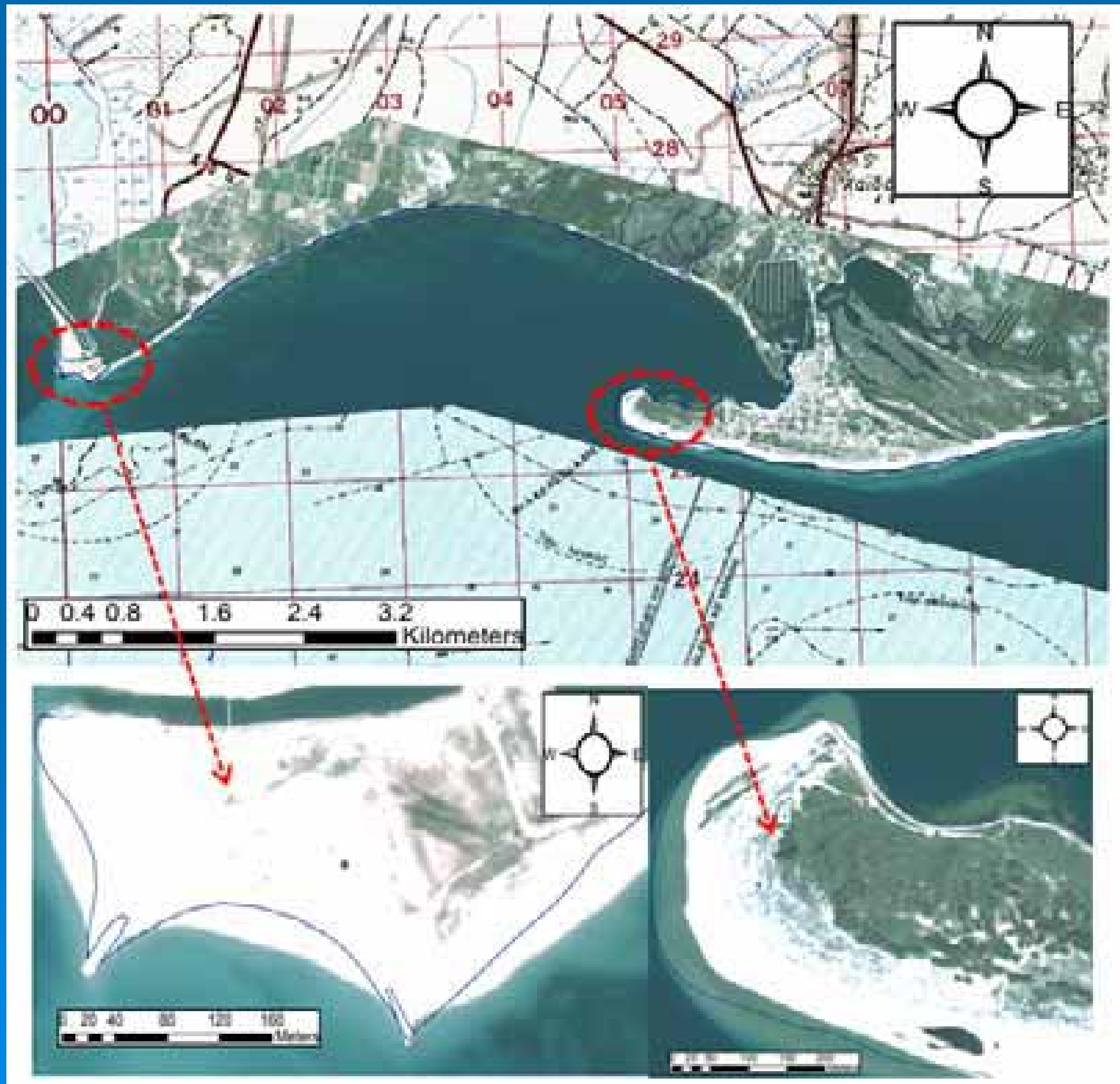
# SHORELINE CHANGE MONITORING

## Digitally extracted shoreline from the high resolution satellite images that correspond to the test region (year 2002), superimposed on the satellite images



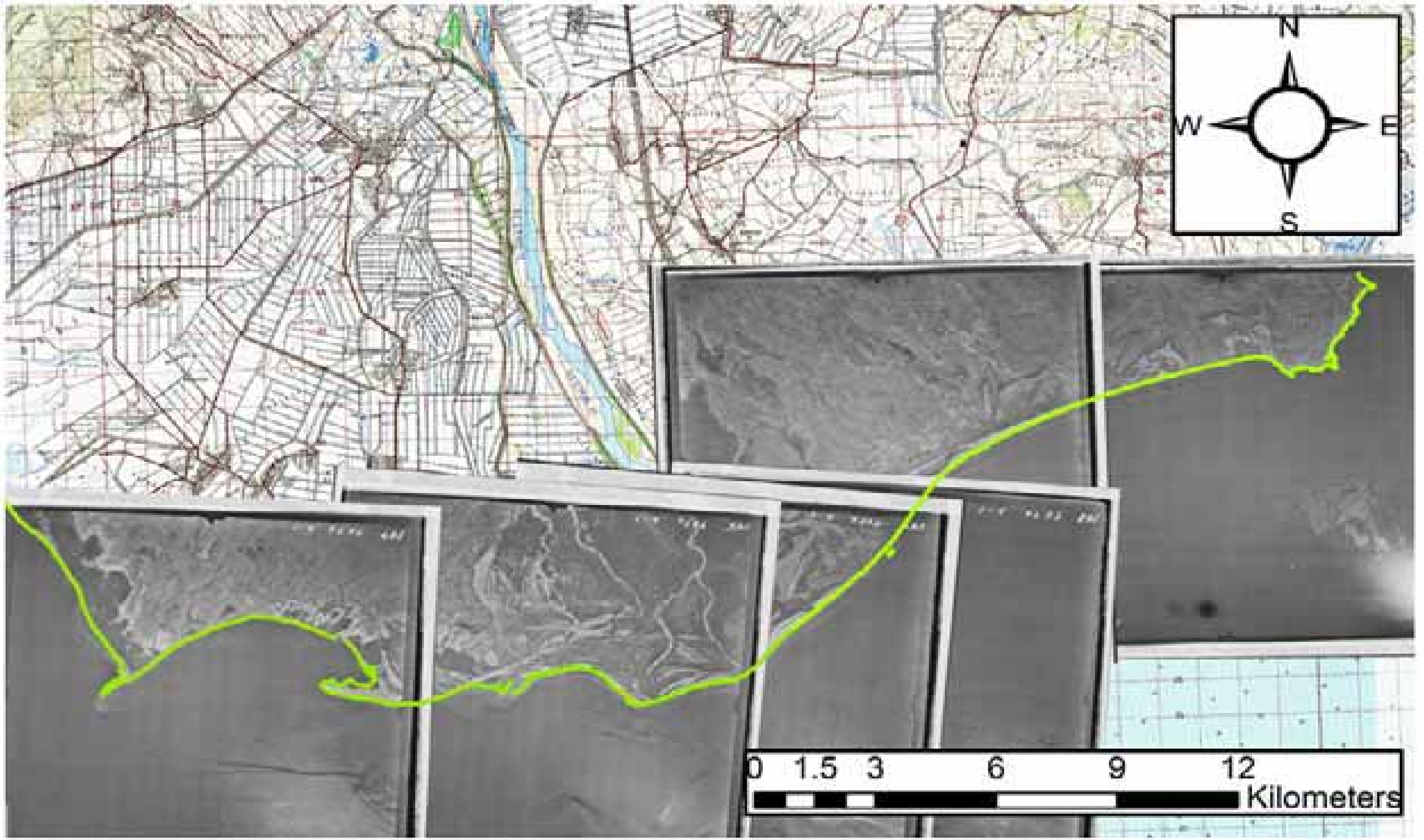
# SHORELINE CHANGE MONITORING

## Digitally extracted shoreline from DGPS field measurements for the test region (year 2007), superimposed on the satellite images (year 2002)



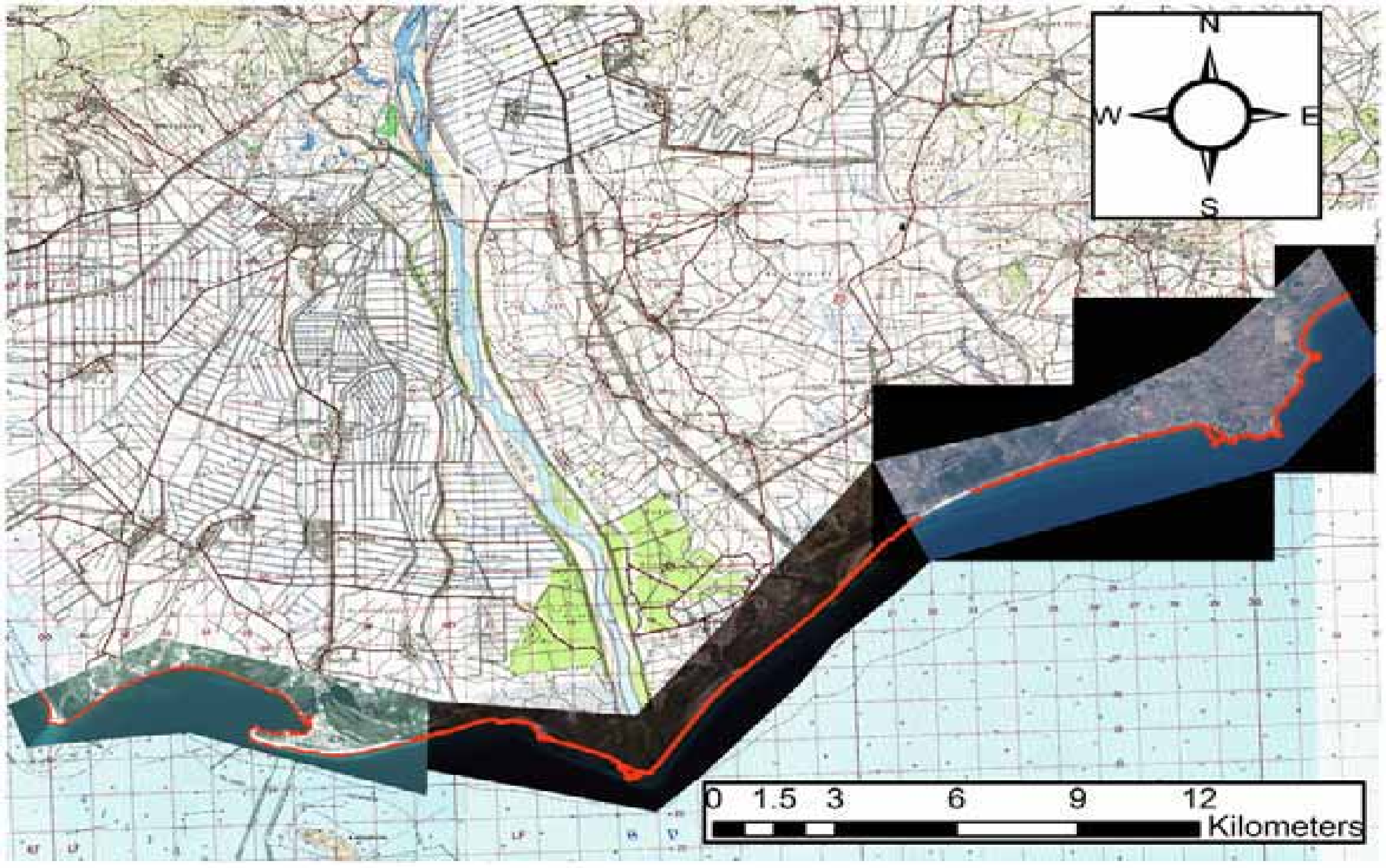
# SHORELINE CHANGE MONITORING

## Digitally extracted shoreline from aerial photographs (year 1945) for the entire pilot study region, superimposed on the aerial photographs



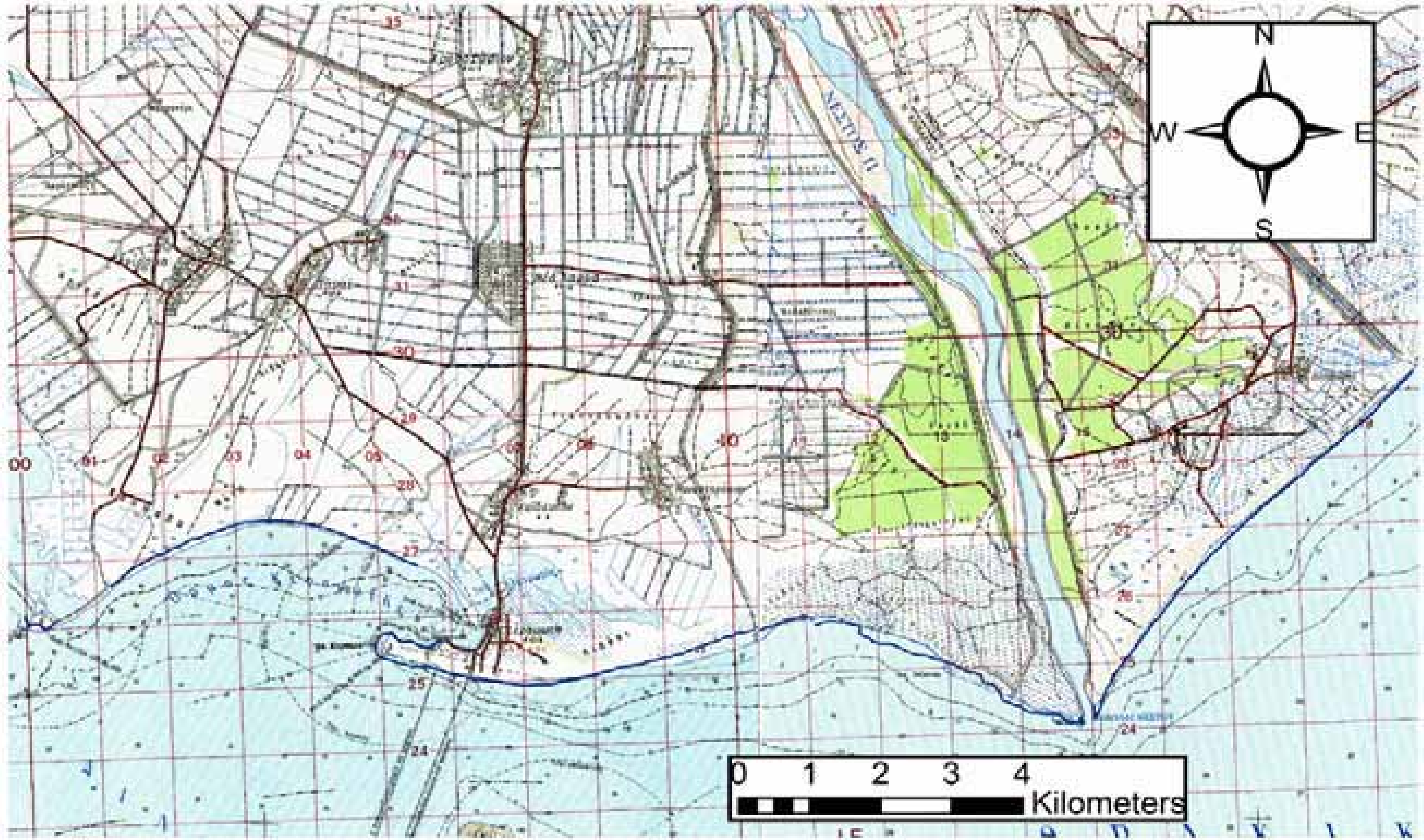
# SHORELINE CHANGE MONITORING

## Digitally extracted shoreline from satellite images (year 2002) for the entire pilot study region, superimposed on the satellite images



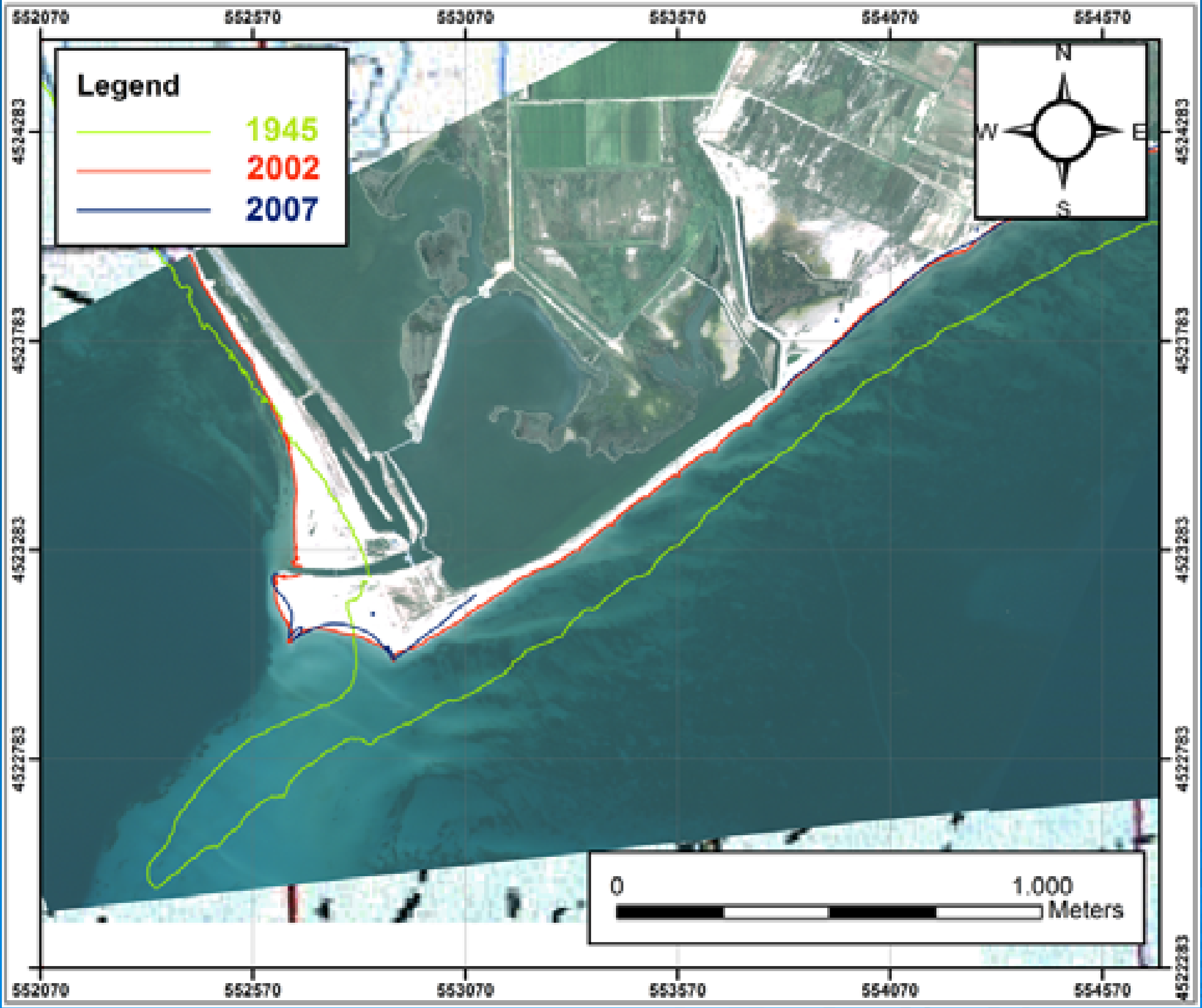
# SHORELINE CHANGE MONITORING

## Digitally extracted shoreline from DGPS measurements (year 2007) for the entire pilot study region, superimposed on the common working background



# HOT SPOTS OF EROSION/ACCRETION

## Shoreline change map for the *Akroneri Cape* region (coordinate system: "Greek Grid")



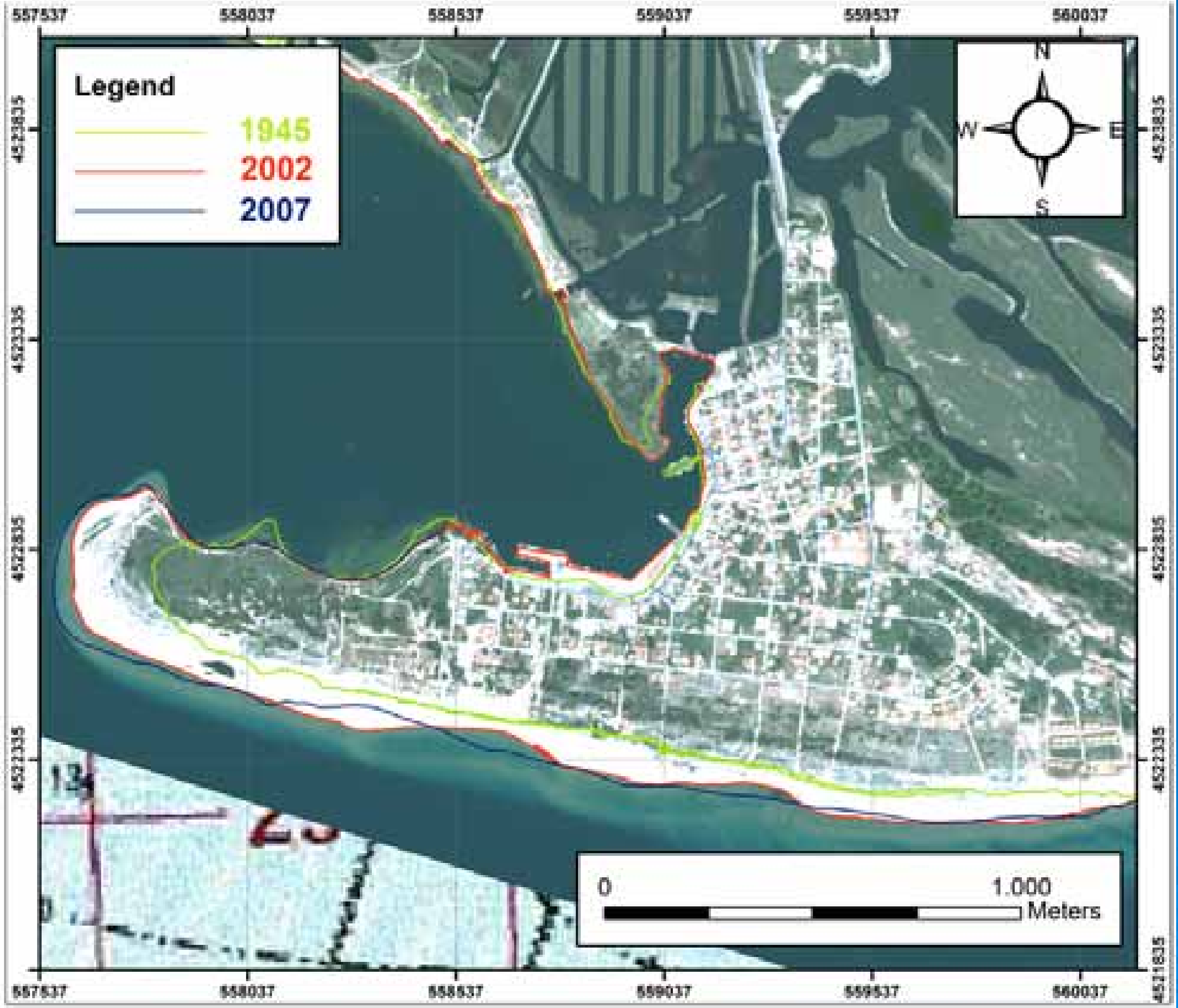

As it can be seen, ***before the construction of the dams (time period 1945-2002)***, the considered region has been mainly subjected to ***severe erosion***, while ***after the construction of the dams (time period 2002-2007)*** it is ***still subjected to erosion*** but at a much ***smaller magnitude***.

| Shoreline evolution (erosion) 1945-2002 | | |
|---|---|---|
| Number of years | Max. erosion (m) | Max. erosion rate (m/year) |
| 58 | 780 | 12.6 |

| Shoreline evolution (erosion) 2002-2007 | | |
|---|---|---|
| Number of years | Max. erosion (m) | Max. erosion rate (m/year) |
| 6 | 27 | 4.5 |

# HOT SPOTS OF EROSION/ACCRETION

## Shoreline change map for the *Keramoti Bay* region (coordinate system: "Greek Grid")



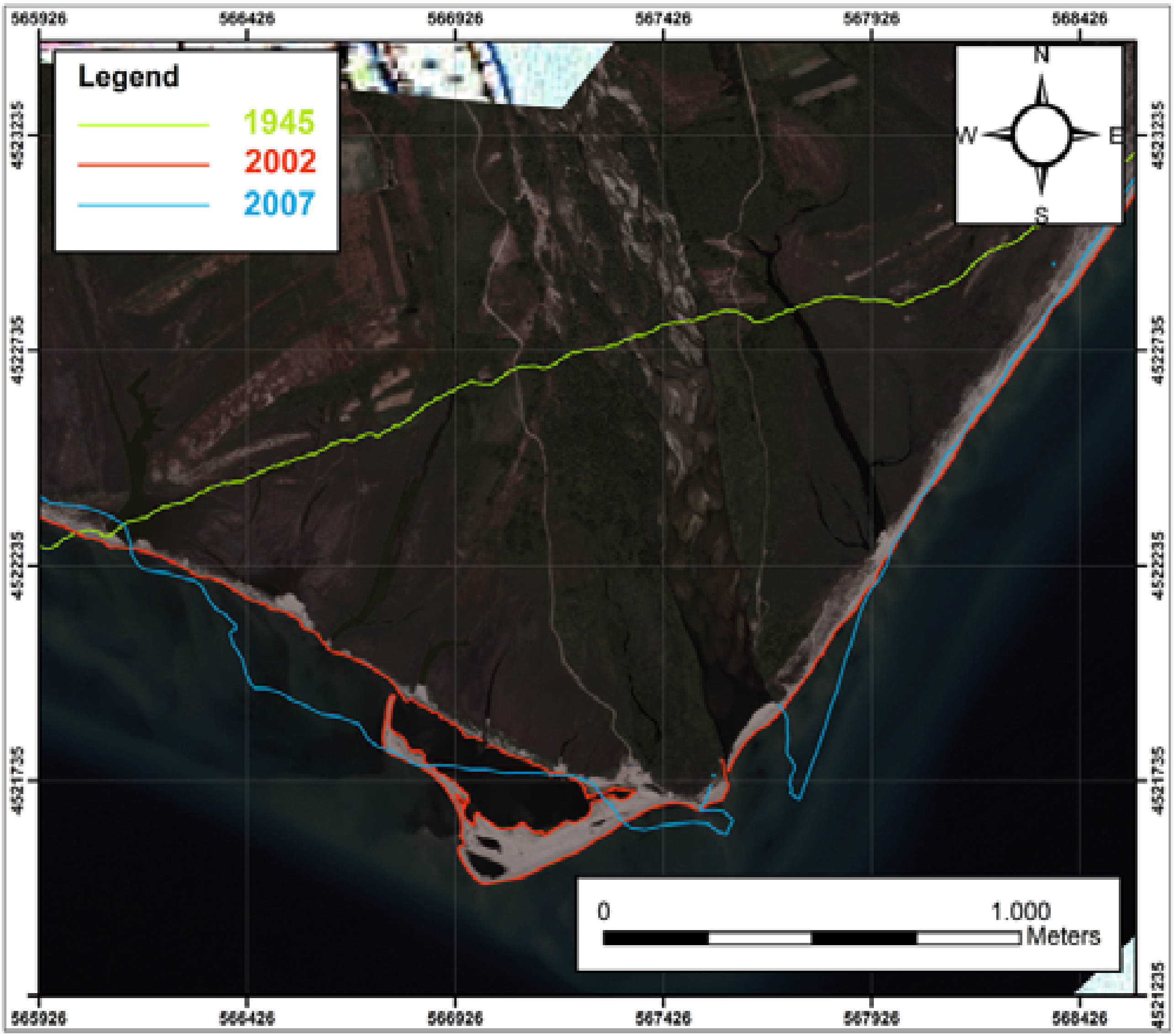

As it can be seen, *before the construction of the dams (time period 1945-2002)*, the considered region has been mainly subjected *to severe accretion*, while *after the construction of the dams (time period 2002-2007)* it is still mainly subjected to *accretion* but at a much *smaller magnitude*.

| Shoreline evolution (accretion) 1945-2002 | | |
|---|---|---|
| Number of years | Max. accretion (m) | Max. accretion rate (m/year) |
| 58 | 250 | 4.0 |

| Shoreline evolution (accretion) 2002-2007 | | |
|---|---|---|
| Number of years | Max. accretion (m) | Max. accretion rate (m/year) |
| 6 | 45 | 7.5 |

# HOT SPOTS OF EROSION/ACCRETION

## Shoreline change map for the Nestos River delta region (coordinate system: “Greek Grid”)




As it can be seen, *before the construction of the dams (time period 1945-2002)*, the considered region has been mainly subjected to *severe accretion*, while *after the construction of the dams (time period 2002-2007)* it is subjected to *both erosion as well as accretion* at a quite *considerable magnitude*.

| Shoreline evolution (accretion) 1945-2002 | | |
|---|---|---|
| Number of years | Max. accretion (m) | Max. accretion rate (m/year) |
| 58 | 1100 | 17.7 |

| Shoreline evolution (accretion) 2002-2007 | | |
|---|---|---|
| Number of years | Max. accretion (m) | Max. accretion rate (m/year) |
| 6 | 180 | 30 |

| Shoreline evolution (erosion) 2002-2007 | | |
|---|---|---|
| Number of years | Max. erosion (m) | Max. erosion rate (m/year) |
| 6 | 160 | 26.7 |

# EROSION – ACCRETION BALANCE

## Eroded/accreted areas for the time period 1945-2002
## (before the construction of the dams)


| | Erosion area ($m^2$) | Accretion area ($m^2$) |
|---|---|---|
| Total area | *1335027.90* | *2242207.82* |
| (%) change | *37.32* | *62.68* |

# EROSION – ACCRETION BALANCE

## Eroded/accreted areas for the time period 2002-2007 (after the construction of the dams)


| | Erosion area ($m^2$) | Accretion area ($m^2$) |
|---|---|---|
| Total area | *374892.96* | *243453.14* |
| (%) change | *60.63* | *39.37* |

## SUMMARY AND CONCLUSIONS

- Nestos is one of the most important transboundary rivers, characterized by its great biodiversity.
- Nestos River flows through two European countries, Bulgaria and Greece, and discharges its water into the Aegean.
- In the Greek part of the river, two dams, the Thisavros Dam and the Platanovrysi Dam, have already been constructed and started operating in 1997 and 1999, respectively.
- The construction of the dams implies a reduction of sediment yield at the outlet of the Nestos River basin and the alteration of the sediment balance of the basin in general, which results to coastal erosion.

## SUMMARY AND CONCLUSIONS

- The mathematical model results indicate that the construction of the considered dams has caused a dramatic decrease (about 84%) in the sediments supplied directly to the basin outlet (delta) and indirectly to the neighbouring coast.

- From the shoreline change monitoring results, it is evident that there are various hot spots in the entire pilot study area, with maximum shoreline evolution rates varying from 4 to 30 m per year both before and after the construction of the dams.

- The decrease in the sediments supplied directly to the Nestos River basin outlet and indirectly to the neighbouring coast, has almost inversed the previous situation, where accretion predominated erosion by 25.36%, just within five years after the construction of the dams, with erosion now predominating accretion by 21.26%.

## SUMMARY AND CONCLUSIONS

- The construction and operation of the Thisavros and Platanovrysi Dams have significantly increased coastal erosion in the Nestos River delta and the adjacent shorelines.

- This fact, together with the anticipated rise of sea level, may pose a great problem to the coastal area resources, threatening the local communities and ecosystems of the considered region.

- It is necessary to further investigate the sediment budget within the estuarine and the adjacent coastal systems and to further monitor erosion/accretion trends of the region for the coming decades.

- Summarizing, the present work constitutes the first quantitative attempt to address the dam sedimentation effect on coastal erosion in the case of Nestos River, combining mathematical modeling with modern remote sensing techniques and field surveying.