# MODELLING THE COASTAL CIRCULATION OF THERMAIKOS GULF, GREECE

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**Abstract**

In this paper we present the setup, calibration, testing, and application of an advanced 3-D coastal circulation model to investigate the contribution of hydrodynamic processes on the formation of eutrophication events in Thermaikos Gulf, *i.e.*, a typical, river-fed, microtidal, semi-enclosed, coastal inlet of the east-central Mediterranean Sea. The effects of long-term meteorological and river discharge conditions on the ocean dynamics of the Gulf are explored numerically by model hindcasts during recent annual cycles. Conducted field observations of *in situ* physicochemical properties in coastal waters support the validation and robust implementation of high-resolution hydrodynamic simulations coupled with river basin modelling of discharge outflows to detect the prevailing coastal circulation patterns.

*Keywords*: Hydrodynamic Modelling; Thermaikos Gulf; Delft3D; WRF; HEC-HMS

## 1. Introduction

Thermaikos Gulf (TG) is an important Mediterranean coastal ecosystem susceptible to several anthropogenic pressures, strong river discharges and variable meteorological and ocean (met-ocean) conditions with local peculiarities, *e.g.*, Vardaris aeolian regime. The latter is a local northerly wind with consistently high intensity, known for the effective advection of cold and dry masses of air above the Vardar/Axios river catchment to the northwestern Aegean Sea via the TG sub-basin. It can play an important role in prevailing coastal circulation patterns especially in the northern part of the TG, which includes the Thessaloniki Bay area. The study area is a typical Euro-Mediterranean, microtidal, rather shallow, semi-enclosed aquatic environment located at the northwestern Aegean Sea (see Section 2.1; Figure 1).

The TG waters are surrounded by a densely populated (~1,500,000 inhabitants) urban environment with several industrial infrastructure units, a commercial port, a big agricultural area within the nearby deltaic region, several aquacultures in coastal waters, and touristic areas, all along the northern part of the coastline. Thus, TG is a rather shallow recipient of various pollution pressures due to many (some of them undefined) diffuse and point sources. The main of them are the four rivers' (Aliakmon, Axios, Gallikos, and Loudias) discharges of nutrient-rich waters and drainage canals, that are fed by rural cultivation runoffs in the coastal plain of a Natura 2000 environmentally protected areas (Figure 1). Secondarily, sources of both processed and untreated wastewater and industrial discharges also affect the coastal seawater and benthic material quality. Accordingly, eutrophication events are quite common in TG, especially along the coastal zone and are of great concern among the general public, municipal and regional authorities, and the scientific community (Genitsaris *et al.*, 2019).

The mesoscale circulation processes of the Gulf are mainly driven by variations of the atmospheric conditions (mostly local temperature and wind regime) *in tandem* with exchanges of seawater masses with the open sea in the Aegean archipelago (Krestenitis *et al.*, 2012). The sub-mesoscale hydrodynamics are mostly determined by the seasonal cycles of river discharges along the western TG coast and the freshwater interaction with the larger scale thermohaline circulation (Androulidakis *et al.*, 2021). The seasonality of hydrodynamic circulation in the TG refers to the cold and hot periods of the year with denser and more saline Aegean Sea Waters (ASW) intrusion usually taking place through the deeper layer along the eastern coasts of the gulf, while lighter lower salinity TG seawater masses generally outflow towards the open sea via the surface layer (Hyder *et al.*, 2002). TG is considered as the main source of brackish waters in the northwestern Aegean, contributing to the general cyclonic circulation of the North Aegean, leading to southerly coastal currents along the west coasts of the TG and the Aegean. Moreover, the TG is a dense water formation area of the east-central Mediterranean basin, led by surface water cooling due to northerly winds (Estournel *et al.*, 2005).

Out of the complex drainage network in the agricultural area of the neighboring deltaic systems of the four rivers, the most significant discharges in the study region are by Axios and Aliakmon. The first regularly has a stronger outflow, more polluted in terms of nutrients, due to fertilizers by adjacent agricultural activities, and a seasonality with peaking discharges during spring and lower flow rates in late August-September (Krestenitis *et al.*, 2012). Aliakmon river's flow is weaker and highly depends on the operational patterns of four consequent dams with hydroelectric power plants (Androulidakis *et al.*, 2021). Therefore, all biochemical properties of seawater in the shallower coastal areas of the TG are eminently influenced by the river plumes' dispersion.

The main motivation of this study is to investigate the influence of generally prevailing and occasionally dominant circulation patterns in the TG related to eutrophication events, based on an integration of three high-resolution modelling components validated by satellite and *in situ* data. Numerical studies worldwide tend to mainly focus on the effects of specific physical properties and processes, such as seawater temperature/salinity and seasonal stratification, coastal upwelling, and inflows of nutrient freshwater on the eutrophication phenomena at coastal waters. We hereby target on the effects of seawater circulation dynamics to trophic conditions in a semi-enclosed coastal ecosystem. This is done by investigating the seasonal or other prevailing hydrodynamic circulation patterns and the water renewal regime in relation to eutrophication events (*e.g.*, HABs formation and red tides) in the study area. The main inquiry goals are to:

- Define ocean circulation patterns that contribute to eutrophication in a typical, weather-driven, microtidal, semi-enclosed gulf of the Mediterranean;
- Relate fine-scale meteorological forecasts to the coastal ocean dynamics during eutrophication events and water renewal periods;
- Build a tool able to predict eutrophication-positive or clear-water dominance physical conditions related to 3-D reproduction of seawater renewal processes.

## 2. Methodology

The presented research endeavor follows an integrated approach to define the detailed 3-D coastal hydrodynamics in a microtidal environment driven mainly by the variability of atmospheric conditions and river outflows (Androulidakis *et al.*, 2021). Therefore, it combines aspects of field monitoring of oceanographic parameters (Androulidakis *et al.*, 2018; Petala *et al.*, 2018), river runoff modelling in several neighboring catchments, downscaled atmospheric modelling of weather conditions in regional scale (Pytharoulis *et al.*, 2015), and fine resolution hydrodynamic modelling of ocean circulation in the coastal marine environment with Delft3D software (Krestenitis *et al.*, 2020) for the 2017-2021 period.

### 2.1 Field data

Seasonal field measurements of physicochemical parameters (currents, temperature, salinity, pH, dissolved oxygen, turbidity, chl-a, nutrients, *etc.*) during a 5-year period from 2017 to 2021 are used to calibrate and validate an ocean circulation model and the plume dynamics of mainly four river outflows in the study area over a set of marine stations and river sites (more recently; see legend of Figure 1 for details) (Androulidakis *et al.*, 2018, 2021). All oceanographic parameters were recorded along the water column with the use of a Conductivity-Temperature-Depth (SBE 19plus V2 SeaCAT Profiler CTD by Sea-Bird Scientific), equipped with:

- Fluorescence sensor (Wet Labs ECP-AFL/FL; mg/m$^3$);
- Dissolved Oxygen sensor SBE 43;
- SBE 27 pH/O.R.P. (Redox) Sensor;
- Turbidity sensor OBS-3 (D&A Instrument Company);
- Altimeter (Teledyne Benthos).

All raw data are processed with SBE Data Processing software of Sea-Bird Scientific company. Preliminary on-board determination of the water column stratification by CTD recordings enabled the seawater sampling from three water column levels (surface, pycnocline, and bottom) with a standard Model 1010 Niskin Water Sampler (1.7 L), in order to investigate the recorded variations of biochemical parameters over the water column depth (Petala *et al.*, 2018). Furthermore, vertical distributions of horizontal currents are also frequently derived with the use of an Acoustic Doppler Current Profiler (ADCP; Workhorse Sentinel by TELEDYNE MARINE) in a moored mode. Thus, field monitored current velocities provide information about the circulation of different water masses and the renewal of the inner-TG.

Except from the riverine water samples collected by our team, river outflow rates were derived from available observation datasets obtained by the Soil and Water Resources Institute (SWRI; Hellenic Agricultural Organization "DEMETER"; https://www.swri.gr/) sustaining stations of the national water resources monitoring network in Greece, as well as TERNA S.A., operating hydropower dams (https://www.ppcr.gr/en/hydroelectric/eleousa-chalkidona-thessaloniki).

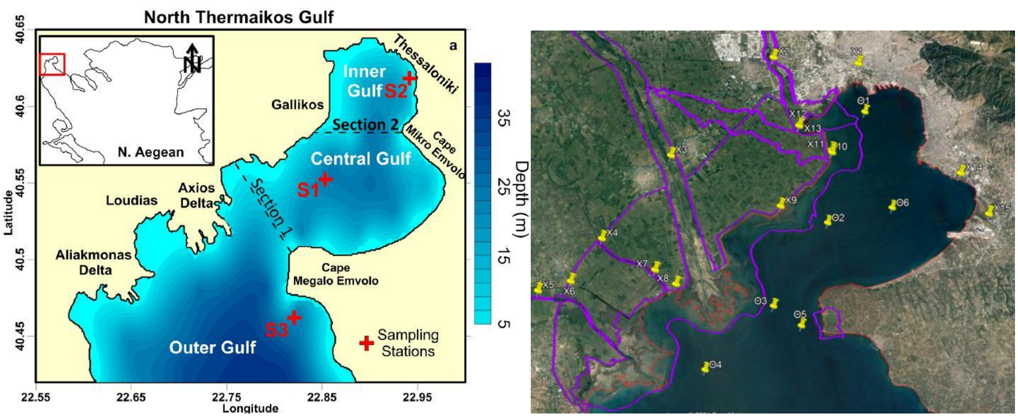


Figure 1. Map of Thermaikos Gulf study area. The sampling stations together with 6 hotspots around the coastal zone are depicted. Left graph: Bathymetric features with sampling stations S1-S3 for 2017-2020 monitoring campaign. Right graph: Sampling stations/sites of the enhanced marine/river (Θ1-Θ6/X1-X15) monitoring campaign for 2021-2022; Natura 2000 protected areas shown with purple hatch.

## 2.2 River basin model

The main freshwater TG input comes from four rivers (Gallikos, Axios, Loudias, and Aliakmon) *in tandem* with a complex system of irrigation canals and trench drains located at its western coast. The Hydrologic Modeling System (HEC-HMS; https://www.hec.usace.army.mil/software/hec-hms/) was used to simulate the hydrologic processes of the river basins mentioned above. This led to detailed simulations of the study area's stream networks (Figure 2), in order to robustly estimate the freshwater outflows in the TG, evaluated by comparisons against *in situ* measured flow rates. The freshwater inflows from the four main rivers discharging into the basin (Aliakmon, Axios, Gallikos, and Loudias; Figure 1) and the drainage outflows, used as lateral input for the Delft3D simulations in TG, were parameterized based on the following:

- Meteorological data: ERA5-Land hourly data, found in: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview
- Digital Elevation Map: EU-DEM v1.1 by the Copernicus platform, found in: https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1/view
- Basic Land Cover data: Corine Land Cover 2018, found in: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018
- Other Land Cover data: Pan-European High-Resolution Layers about imperviousness, forests, grasslands, water bodies & wetness, small woody features by the Copernicus platform, found in: https://land.copernicus.eu/pan-european/high-resolution-layers
- Soil Data: 3-D Soil Hydraulic Database of Europe at 1 km and 250 m resolution, found in: https://esdac.jrc.ec.europa.eu/content/3d-soil-hydraulic-database-europe-1-km-and-250-m-resolution
- European Soil Database, found in: https://esdac.jrc.ec.europa.eu/content/european-soil-database-derived-data
- Aliakmon Dams overflow/outflow estimated from electricity production data and the daily degree of reservoir filling, derived from: https://www.admie.gr/agora/statistika-agoras/dedomena

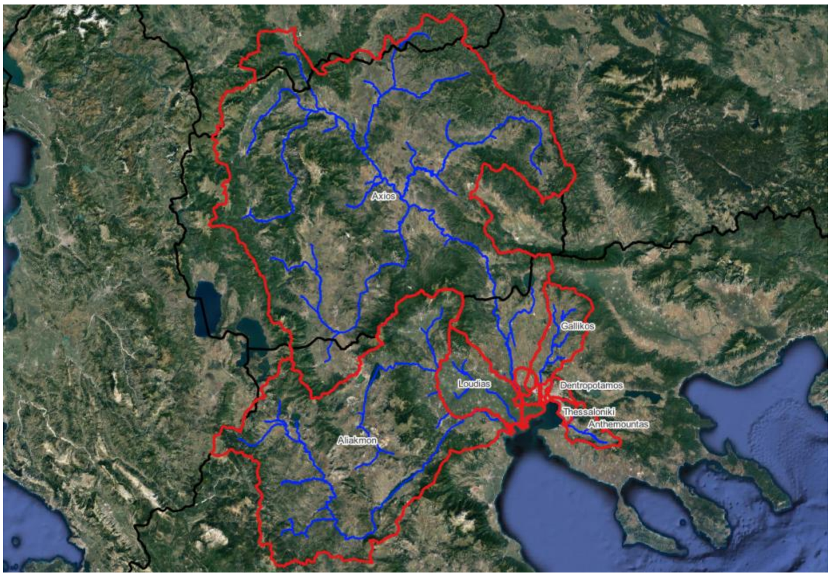


Figure 2. Map of the multi-catchment adjacent domains of AUTh's river/torrent basin model HEC-HMS around the TG.

## 2.3 Atmospheric modelling of meteorological conditions

The meteorological forcing of the Delft3D coastal hydrodynamic model was derived from the met-ocean weather forecast operational system Wave4Us (Krestenitis *et al.*, 2014, 2015; http://wave4us.web.auth.gr). Simulations of regional-scale, high-resolution, atmospheric circulation were conducted with the Weather Research and Forecasting model's Advanced Research dynamic solver (WRF-ARW-AUTh). The integrated weather forecast system relies on three nested meteorological simulations with increasing resolution, i.e., over the European continent (D01), the central Mediterranean (including Apennine and Balkan peninsulas; D02), and Central Macedonia (D03; Figure 3). The produced 3-hourly atmospheric datasets (wind velocities, sea level pressure, air temperature, relative humidity, cloudiness, latent and sensible heat, precipitation) cover the finer scale domain with a resolution of 1,67 km (Pytharoulis *et al.*, 2015). Meteorological observations for the study period, including temperature, precipitation, wind speed and direction, were obtained from AUTh's station; wind datasets were used to examine prevailing wind patterns during the study period. Additionally, recorded precipitation values were used to investigate the contribution of rainwater to seawater's physical variables' distribution and to characterize the surficial buoyant discharges. WRF-ARW is set to use high-resolution 30′′×30′′ topography and land use coverage (derived from the USGS database), 39 vertical sigma levels up to 50 hPa, initial and lateral boundary conditions from GFS/NCEP analysis and 3-hourly forecasts of 0.25°×0.25° resolution, and daily Sea Surface Temperatures of 0.083°×0.083°, with initial time at 12:00 UTC and a daily forecast horizon of 4 days. The microphysical processes and the unresolved-scale cumulus convection in D01, D02 are modelled by the Ferrier and the Betts-Miller-Janjic schemes. The longwave/shortwave radiation is parameterized by the Rapid Radiative Transfer Model (RRTMG). The Mellor-Yamada-Janjic and the NOAH Unified model represent the boundary layer processes and soil physics.

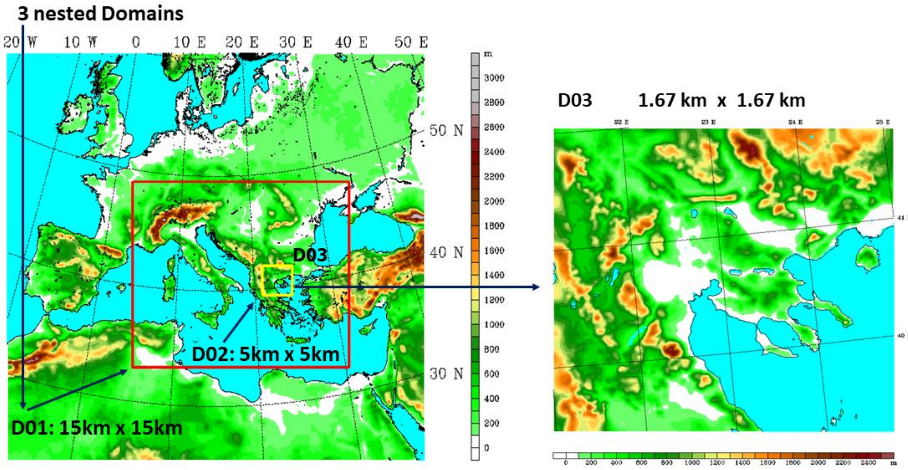


Figure 3. Map of the 3 nested domains of AUTh's Numerical Weather Prediction System based on WRF-ARW operational forecast simulations over Europe (15km), its south-central part including the central Mediterranean (5km), and the central part of Greek Macedonia (1.67km) around the TG (north-western Aegean Sea).

## 2.4 Ocean modelling of coastal circulation

The coastal circulation simulations were implemented with the FLOW module of the Delft3D (Delft3D-FLOW) modeling system (https://oss.deltares.nl/web/delft3d) in a 3-D sigma-layer configuration (Krestenitis *et al.*, 2020). The model solves numerically the 3-D non-linear shallow water equations, derived from the Navier-Stokes equations for incompressible free-surface flow. Apart from the horizontal equations of motion, the system of model equations consists of the continuity equation and the transport equations for conservative constituents. Real-world applications' validation and model description of Delft3D-FLOW can be found in Gerritsen *et al.* (2007).

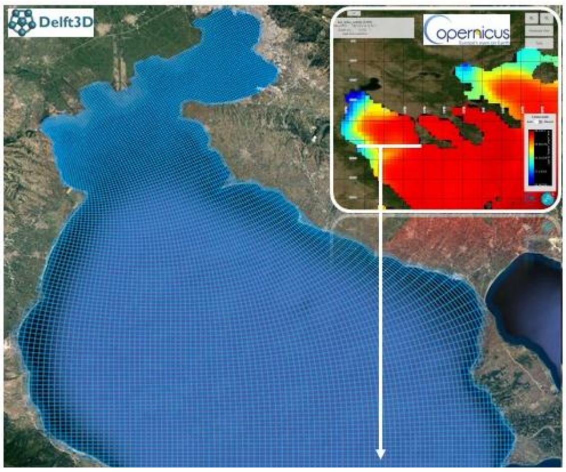


Figure 4. Map of the ocean model (Delft3D) domain (curvilinear grid) for high-resolution simulations of hydrodynamic circulation in the TG. Position of the domain's southern boundary with operational forecast boundary conditions by the Copernicus CMEMS.

In this study, the model domain of Delft3D-Thermaikos covers the TG (22.55–23.374°E and 39.96–40.643°N) and is defined by a 110×126 curvilinear grid, with a resolution step varying from about 750 m offshore near the open boundary (northwestern Aegean Sea) to less than 350 m in the inner gulf (Figure 4). 15 sigma layers were used to vertically discretize the water column. The sigma-layers configuration allows model coordinates to follow the bottom morphology and is suitable for Mediterranean coastal regions with shallow and complex topography (Zavatarielli and Mellor, 1995). The boundary conditions, *i.e.*, physical properties in the water column along the open southern boundary of the TG model, are derived by the Mediterranean Forecasting System model (Clementi *et al.*, 2019; http://medforecast.bo.ingv.it/) embedded into Copernicus CMEMS Mediterranean Sea Physical Reanalysis dataset (Simoncelli *et al.*, 2019). Androulidakis *et al.* (2021) discuss in detail the model setup (*e.g.*, initial, boundary, and forcing conditions; parameterization and river input) and its performance capabilities.

## 3. Models' Validation

A lot of work has been done in the recent past to validate the individual modelling components of the integrated met-ocean hydro-weather prediction system in the TG. Herein we present aspects of the models' evaluation and their parameterizations and finetuning.

### 3.1 Atmospheric model (WRF-ARW-AUTh) evaluation

Statistical evaluation has been performed using data from 17 available meteorological stations of the Hellenic National Meteorological Service. These stations cover Greece, including Thermaikos Gulf. Figure 5 presents the Mean Error (ME) and the Mean Absolute Error (MAE) of WRF-ARW D02 forecasts, relative to the observations (as a function of forecast time), for a full annual cycle from spring 2014 to winter 2015 over Greece. The Mean Sea Level Pressure (MSLP) is underestimated, while the minimum (maximum) daily temperatures are overestimated (underestimated). The MAE of MSLP increases with forecast time from 0.8 to 2.1 hPa, while that of air temperature lies between 1.6 and 1.9 °K. The wind speed at 10 m (not shown) is overestimated and its MAE varies from 2.1 to 2.5 m/s. The predictability of air temperature and wind speed (not shown) is conserved with forecast time (Pytharoulis *et al.*, 2015).

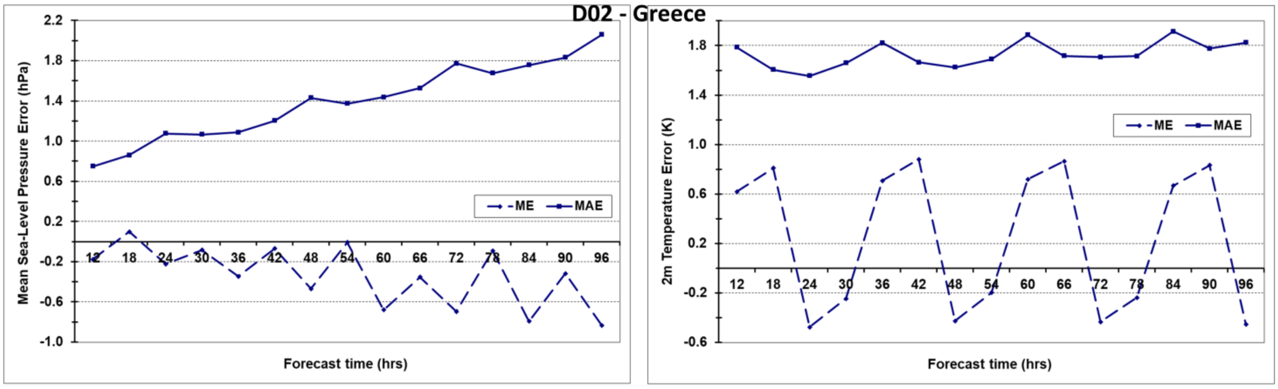


Figure 5. Mean Error (ME) and Mean Absolute Error (MAE) of the WRF-ARW D02 predicted MSLP (hPa) and air Temperature (°K) at 2 m above ground, against the observations of 17 Greek meteorological stations, from spring 2014 to winter 2015.

### 3.2 River basin model (HMS) validation

Figure 6 presents comparisons of HEC-HMS simulated flow rates against observed field data for a full annual cycle during 2018 in Aliakmon River basin. The validation of the implemented hydrologic model was based on the only available monitoring station of SWRI (see Section 2.1) near the estuary of Aliakmon River. Figure 6 presents comparisons of HEC-HMS simulated flow rates against observed field data for a full annual cycle during 2018 in Aliakmon River basin. Moreover, several model skill metrics corroborate the acceptable performance of HEC-HMS: Coefficient of determination $R^2$=0.69, Pearson correlation $R_p$=0.83, Root-Mean-Square-Error to Standard Deviation RMSE/STDEV=0.69, Nash Sutcliffe model efficiency NS=0.52, Percent Bias PB=15.88%.

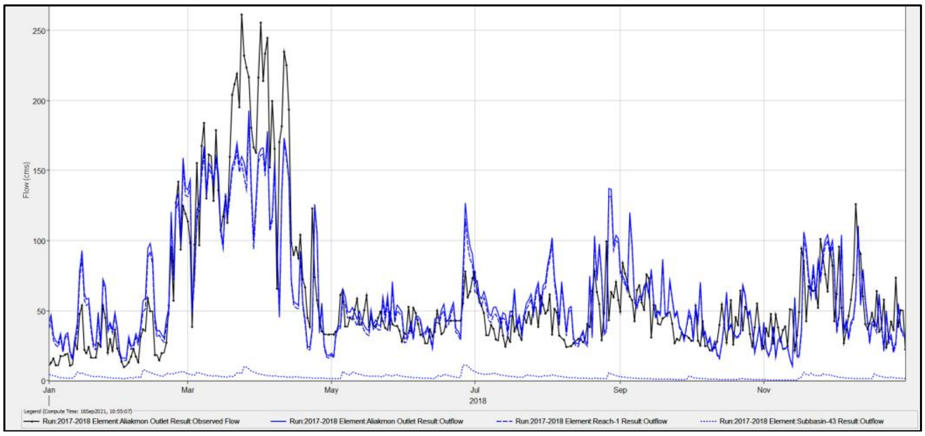


Figure 6. Comparisons of HEC-HMS simulated flow rates (cms: $m^3/s$) [blue color lines] against observed field data [black line] for a full annual cycle during 2018 in Aliakmon River basin.

### 3.3 Hydrodynamic model (Delft3D) validation

Characteristic comparisons of spatially averaged (over the entire TG) Sea Surface Temperature (SST) from model simulations with Delft3D-Thermaikos against satellite data by GHRSST (https://www.ghrsst.org/), with and without the influence of the seasonal cycle during 2017-2021 are provided in Figure 7. Quantitative model skill metrics are also provided referring to the Pearson correlation coefficient, Rp, and root-mean-square-error, RMSE, along with the Sen's slope nonparametric estimator (Sen, 1968) that defines statistically significant trends in univariate timeseries, being resistant to outliers. The Delft3D-Thermaikos model prediction skill is quite high for the 4-year hindcsast period. The correlation coefficients for both seasonal and non-seasonal comparisons are high and statistically significant ($p$-value < 0.001). The RMSE is 0.96°C for the seasonal timeseries and approximately 0.5°C for the timeseries without the seasonal cycle. Increasing SST trends were derived for all timeseries. Especially the Sen's slopes of the non-seasonal SST timeseries are identical. The model validation against satellite observations confirms the good performance of the model to simulate both the seasonal cycle of temperature and the extreme values (peaks and lows) that may occur during the annual cycle.

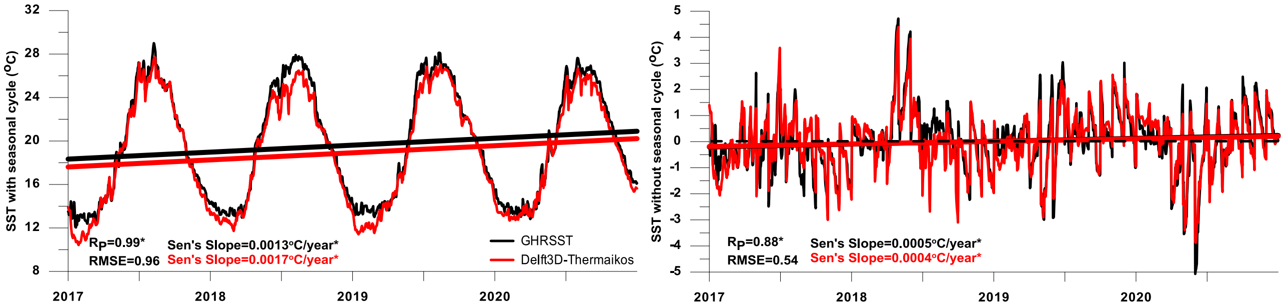


Figure 7. Comparisons of spatially averaged (over the entire TG) SST from model simulations with Delft3D-Thermaikos (red line) against satellite data by GHRSST (black line), with and without the seasonal cycle (left and right graph, respectively), during 2017-2021. Pearson correlation $R_p$ and RMSE (°C) are provided along the Sen's slope. Asterisks (*) indicate statistical significance of correlation comparisons and Sen's Slopes based on Mann-Kendall test ($p$-value < 0.001).

## 4. Results

### 4.1 Results of river runoff estimations

The estimated surface runoffs, as they are derived from the hydrologic models for the five rivers that outflow in TG, are presented in Figure 8. The most significant outflows are from Aliakmon and Axios rivers, while the rest of the fluvial discharges show "order of magnitude" weaker rates.

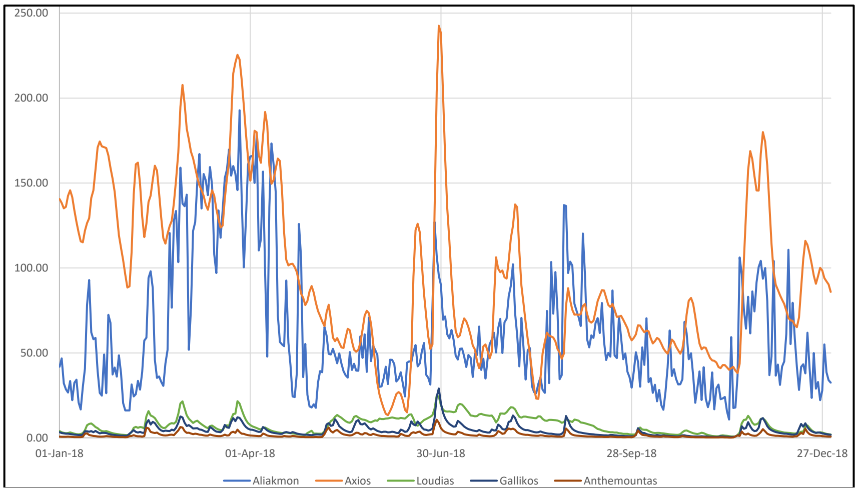


Figure 8. HEC-HMS simulated flow rates (cms: $m^3/s$) for a full annual cycle during 2018 within the five main river basins in the TG area.

### 4.2 Results of ocean modelling hindcasts

Characteristic results derived from the Delft3D-Thermaikos simulations are provided during two significant eutrophication events in mid-summer and early-winter of 2017 (Genitsaris *et al.*, 2019) under southerly winds, and two renewal events in the summer/autumn periods under northerlies (Androulidakis *et al.*, 2021).

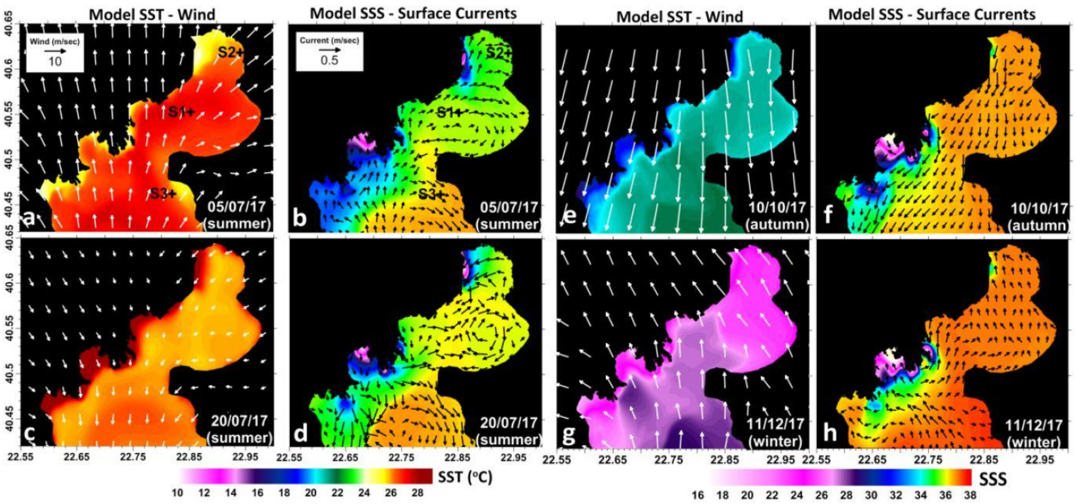


Figure 9. Maps of Sea Surface Temperature (SST; °C) and Salinity (SSS) by Delft3D simulations in Thermaikos Gulf, overlaid with wind fields (white vectors; m/s) by WRF-AUTh model in contrast with simulated surface currents (black vectors; m/s) during 2017.

### *4.2.1 Prevailing Coastal Circulation Patterns*

Figure 9 presents horizontal distribution maps of SST and Sea Surface Salinity (SSS) by Delft3D simulations in TG, overlaid with wind fields by WRF-ARW-AUTh model in contrast with simulated surface currents during 2017. The southerly winds induced a general northward spreading of surface waters imposing anticyclonic circulation patterns. SSS revealed smaller values in the inner- and central-TG (35; Figure 9b) than the outer-TG (36.5; Figure 9b) in agreement with *in situ* observations collected on July 5 in Stations S2 and S3, respectively (Androulidakis *et al.*, 2021). Two distinct circulation features emerged from the surface current fields; an anticyclonic pattern in the central- and inner-TG and a second anticyclonic eddy in the outer-TG, keeping the two water masses separated. Stronger northerly winds, that prevailed in mid-July played a role on the southward advection of the riverine plume, away from the northern central- and inner-TG regions (Figure 9d). A short period of strong northerly winds in mid-July also played a role on the different eutrophication levels and vertical distributions of physical parameters. During the eutrophication event in early-winter of 2017, the prevailing southerly winds (Figure 9g) induced a respective northward surface circulation pathway (Figure 9h).

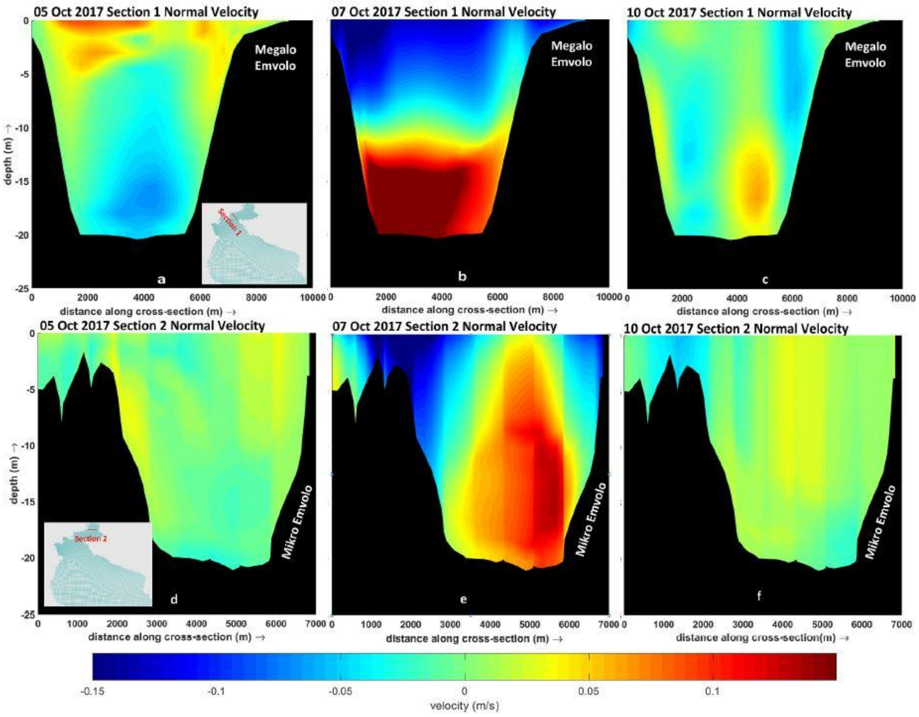


Figure 10. Vertical distribution of normal velocity (m/s) on (a) 5/10/17, (b) 7/10/17, (c) 10/10/17 across Section 1 and (d) 5/10/17, (e) 7/10/17, (f) 10/10/17 across Section 2, as derived by the Delft3D-Thermaikos simulation. Sections 1 and 2 are marked on the insert maps at panels (a) and (d), respectively.

#### *4.2.2 TG seawater renewal event (October 2017)*

The vertical distribution of the current velocities during the renewal event of October 2017 is presented in Figure 10. The southwestward spreading of the northern TG's surface waters during the renewal event of October was detected at the upper 10 m of Section 1 (Figure 10b). On October 7, the southwestward moving upper layer was very thick with strong velocities (0.15 m/s; Figure 10b) at the west side of the passage (along the Axios Delta) that connects the central- with outer-TG. Similarly, northeastward currents occurred between 10 and 20 m of depth. Especially at the east side of the passage, the thickness of this layer is even larger (5 m to bottom), confirming the cyclonic circulation that may improve the renewal of the TG in agreement with Hyder et al. (2002) and Krestenitis et al. (2012). On October 10, a strong northeastward flow was detected in the deeper layers of the eastern part of Section 1, indicating the inflow of deeper open sea waters into the central-TG (Figure 10c). On the contrary, the near-surface layer was characterized by clear northward currents a few days earlier (e.g., October 5; Figure 10a), when weak southerly winds prevailed. The northward flow between the inner- and central-Gulf (Section 2) was stronger on October 7, covering almost the entire central and eastern parts of the passage (Figure 10e). Simultaneously, strong southward flows (~0.15 m/s) occurred along the western coasts associated to the general cyclonic circulation.

## 5. Conclusions

The eutrophication events were mainly associated with the dominance of southerly winds, which affect the ocean circulation over the TG threefold: a) they confine the surface waters in northern TG, separating the waters masses meridionally; b) they contribute to the northward spreading of nutrient-rich brackish waters towards the northern parts of TG; c) they impose an anticyclonic circulation, especially in the inner- and central-Gulf weakening its renewal process. Northerly winds contribute on the renewal of the Gulf imposing a two-layer flow and cyclonic circulation, especially along the eastern coasts. Therefore, new insight is provided on the mesoscale oceanic circulation and the sub-mesoscale local hydrodynamic effects on marine eutrophication events.

**Acknowledgments**

Part of the presented research was conducted within the project "Mapping of pressures and estimation of external and internal loads of nutrients and organic material for the protection and management of the marine waters in Thermaikos Gulf".

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