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SURFACE FLOW, URBAN AND LAND-BASED POLLUTION LOADS IN DAVUTLAR BAY

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ABSTRACT
Coastal areas are heavily influenced by human actions such as urbanization of natural and agricultural areas. Besides pollution loads in discharges of the urban and industrial wastewater, loads washed off from the land are the main sources of coastal pollution, both of which can have deteriorating effect for the environment. The point and non-point pollutants have become a growing concern for Davutlar bay, a tourism district in the eastern Aegean Sea urbanized in the last decades. In order to reduce the pollution in the bay, the construction of a wastewater treatment plant has started in 2013. In this study, the surface discharges from the surrounding basin towards the bay are modelled and the pollutants buildup in surrounding basin are calculated by using Environmental Protection Agency's Storm Water Management Model (SWMM) for the year 2018 considering different landuses defined in the CORINE system. The wastewater pollutants, namely total suspended solids (TSS), biological oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (NT) and total phosphorus (PT); discharged from the urban area to the bay are calculated before and after the wastewater treatment plant began to operate in 2018. The effects of land-based pollutants and the reducing effect of the wastewater treatment plant for the coastal pollution are discussed in the projections for the year 2019.

Keywords: *Coastal Pollution, CORINE, Runoff, Water Quality, SWMM model*

1. INTRODUCTION

Davutlar bay located in the south of Aydın Province, Kuşadası District is a coastal area with a coastal line exceeding 10km and a large agricultural basin at the eastern side of the coastal line (Fig. 1.). The coastal line with the district center of Kuşadası in the north and with the villages of Güzelçamlı in the south and of Soğucak, Yaylaköy, Caferli, Davutlar and Ağaçlı in the east accommodates a large population particularly during summer. In areas, where wastewater is discharged to the bay, the winter population is 38,803, based on the 2017 data of Turkish Statistical Institute (TURKSTAT, 2018). While the population data cites the winter population, it is estimated that the population of the area exceeds 500,000 in the high season.

Fig.1. Davutlar bay (Google Earth, 2018)

As a result of increasing urbanization since 1980’s, agricultural lands have been gradually transformed into low-density urban settlement areas up to approximately 2km’s inwards from the coastal line towards east. In these settlement areas where majority of the summer population resides, urban wastewaters are discharged into the sea without any treatment. It is the major source of the coastal pollution in the bay. Advanced Biologic Treatment will be provided when the currently incomplete Kuşadası Wastewater Treatment Plant is put into operation. The Phase I of the plant will operate with a capacity adequate for serving 333,800 individuals and treating 89,794m^3 of wastewater daily. The Phase II will serve 477,100 individuals with a daily wastewater treatment capacity of 125,548 m^3 (ASKI, 2017).

2. MATERIAL AND METHODS

2.1. Processing of the geographical data

The basin surrounding the Davutlar bay, which has a total basin area of 188.17km^2, is divided into 5 sub-basins. The surface flow in sub-basins 2, 3 and 5 drains into the bay after being collected in three streams called Ağaçlı Brook, Yörük Brook and Bal Creek, respectively. Sub-basins 1 and 4 drain without forming a surface stream. The altitude map and the borders of the basin surrounding the bay are shown in Fig. 2.

Fig. 2. The altitude map and the borders of the basin surrounding the Davutlar bay

The geographical information related to the basin is interpreted by using the ArcGIS data. Topographic data of the land are obtained using the Advanced Spaceborne Thermal Emission and Reflection Radiometer, Global Digital Elevation Model version 2 (ASTER GDEM v.2) with 72m horizontal resolution (ASTER GDEM Validation Team, 2011). The mean inclinations of the sub-basins are calculated with ArcMap v.10.2.2 tools on DEM topographic maps.

The sub-basins are divided into smaller subcatchments in the model based on the type of landuse defined in CORINE classification system. Accordingly, 1,815.55ha of the basin area consists of artificial surfaces, 8,078.85 ha consist of agricultural lands, and 8,922.93ha consists of forests and semi-natural areas. Distribution of lands within the basin is given in Fig. 3. Types of landuse in the sub-basins are summarized in Table 1.

2.2. Hydrological Modelling

The flow rates of surface streams and distributed pollution loads in the sub-basins surrounding the bay are determined by using SWMM v5.1. The SWMM is a simulation model for surface flow hydraulics and water quality for short or long periods with dynamic wave method. It performs hydrologic, hydraulic and water quality simulations for surface flows. SWMM gestates the subcatchment as a rectangular surface area that has a uniform slope S and a width W. This area drains the precipitation to a single outlet as shown in Fig. 4.a. Overland flow is generated by modeling the subcatchment as a nonlinear reservoir, which experiences inflow from precipitation and losses from evaporation and infiltration (Fig. 4. b).

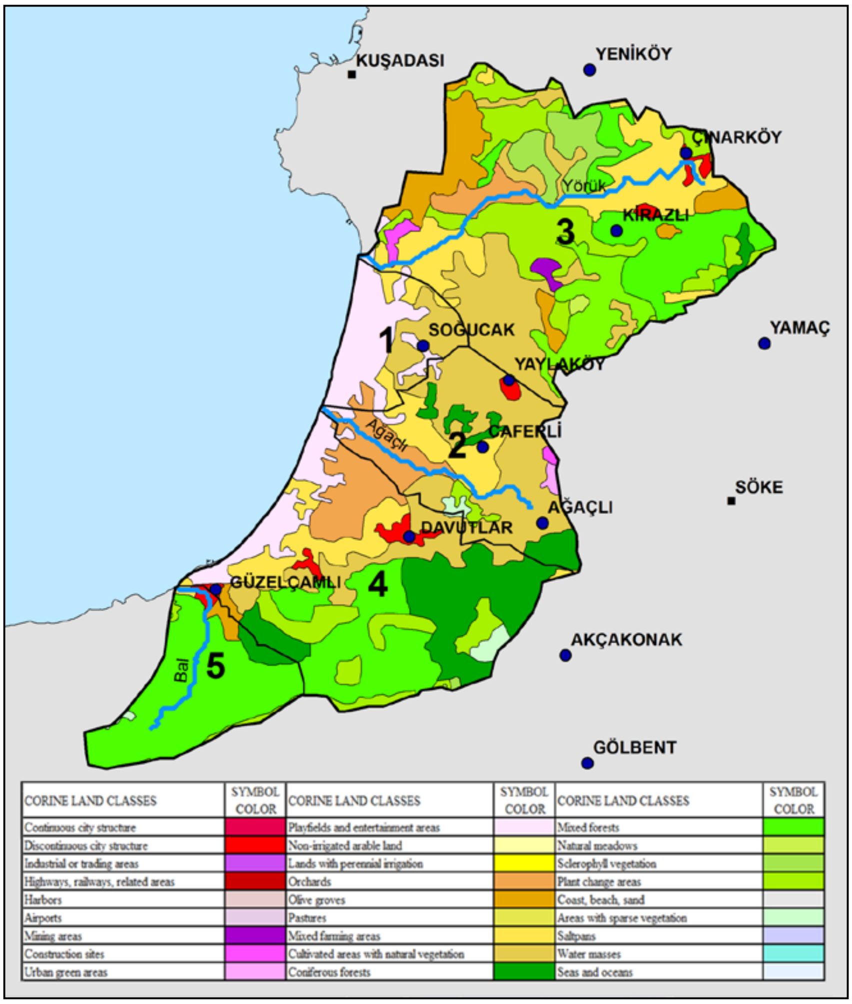

Fig. 1. Landuse in the basin according to CORINE

Table 1. Types of landuse in the surrounding basins

Corine Landuse Classes		Area (ha)				
Level-1	Level-3	Sub-Basin -1	Sub-Basin -2	Sub-Basin-3	Sub-Basin-4	Sub-Basin-5
1. Artificial surfaces	1.1.2. Discontinuous urban fabric	-	35.98	72.63	138.58	33.04
	1.3.1. Mineral extraction sites	-	-	50.55	-	-
	1.3.3. Construction sites	-	18.21	61.39	-	-
	1.4.1. Green urban areas	-	33.84	-	-	-
	1.4.2. Sport and leisure facilities	728.69	81.12	36.14	524.08	-
2. Agricultural areas	2.2.2. Fruit trees and berry plantations	39.67	383.20	248.18	475.34	-
	2.2.3. Olive groves	-	-	716.93	36.22	61.99
	2.4.2. Complex cultivation patterns	145.72	432.04	1,250.75	577.92	16.41
	2.4.3. Land principally occupied by agriculture with significant areas of natural vegetation	361.53	1,460.47	1,278.91	587.83	-
3. Forest and semi-natural areas	3.1.1. Broad-leaved forest	-	-	657.19	-	-
	3.1.2. Coniferous forest	-	292.50	60.09	1,187.88	85.10
	3.1.3. Mixed forest	-	-	1,192.49	1,151.47	1,625.63
	3.2.1. Natural grasslands	-	-	27.07	-	-
	3.2.3. Sclerophyllous vegetation	-	-	450.83	12.16	-
	3.2.4. Transitional woodland-shrub	-	65.72	1,347.31	580.24	51.25
	3.3.3. Sparsely vegetated areas	-	34.47	-	82.13	11.80
5. Water bodies	5.2.3. Sea and ocean	0.65	-	-	0.62	-
	Total	1,276.27	2,837.55	7,450.47	5,354.45	1,885,21

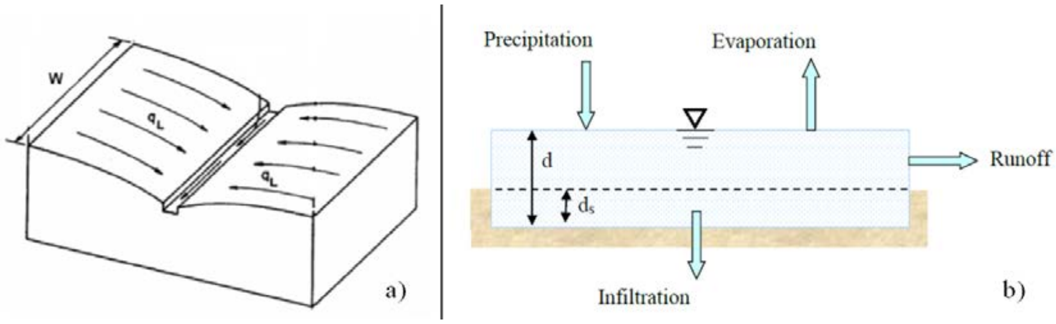

Fig. 4. a) Idealized representation of a subcatchment b) Nonlinear reservoir model of a subcatchment (Rossman and Huber, 2015).

From conservation of mass, the net change in depth d per unit of time t is calculated as the difference between inflow and outflow rates over the subcatchment as in Eq. (1), where i is rate of rainfall + snowmelt (mm/s), e is the surface evaporation rate (mm/s), f is the infiltration rate (mm/s), q is the runoff rate (mm/s) per unit area.

$$\frac{\partial d}{\partial t} = i - e - f - q \qquad (1)$$

The outflow across the subcatchments surface is assumed to behave as an uniform flow within a rectangular channel of width W (m), height d–ds, and slope S, the Manning equation can be used to express the runoff's volumetric flow rate Q (m^3/s) as in Eq.(2).

$$Q = \frac{1}{n} \cdot W \cdot S^{1/2} \cdot \left(d - d_s\right)^{5/3} \qquad (2)$$

The runoff flow rate per unit surface area of the subcatchment, q (m/s) is as in Eq. (3).

$$q = \frac{1}{A \cdot n} \cdot W \cdot S^{1/2} \cdot \left(d - d_s\right)^{5/3} \qquad (3)$$

After replacement Eq. (3) in Eq. (1), the mass balance relation becomes an ordinary nonlinear differential equation as in Eq. (4) (Rossman and Huber, 2015).

$$\frac{\partial d}{\partial t} = i - e - f - \left[\frac{1}{A \cdot n} \cdot W \cdot S^{1/2}\right] \left(d - d_s\right)^{5/3} \qquad (4)$$

The time step (Δt) of the simulation is set for the precipitation excess above the depression storage depth of the subcatchment. The total runoff Q from the subcatchment at the end of the time step is calculated by using a standard fifth-order Runge-Kutta integration routine with adaptive step size control (Press et al., 1992) to solve the equivalent of Eq. (4).

The 3 year averaged daily precipitation data from nearest 3 stations (İzmit-17066, Gölcük-17067 and Başiskele-18409) is used in the model. In this way, the intensity of seasonal precipitation could also be simulated in the model.

2.2. Hydrodynamic Modelling

Hydrodynamic solution of SWMM is based on a node-link network and the one-dimensional, gradually varied, unsteady flow throughout it. The model solves the conservation of mass (Eq.5) and momentum (Eq.6) for unsteady free surface flow (St. Venant equations) to determine the water level at each node and the flow rate and flow depth within each link at each time step of the simulation period. The one dimensional flow under hydrostatic pressure is assumed to be formed in a channel with a bed slope close to unity and boundary friction can be represented in the same manner as for steady flow (Rossmann, 2017). Here, A (m^2) represents cross-sectional area of the conduit or channel; H, hydraulic head of water in the conduit (m); S_f = friction slope (head loss per unit length) and g = acceleration of gravity (m/sec^2).

$$\frac{\partial d}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad (5)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial (Q^2/A)}{\partial x}+g\cdot A\cdot\frac{\partial H}{\partial x}+g\cdot A\cdot S_f=0 \qquad (6)$$

On the other hand, the friction slope S_f can be expressed in terms of the Manning equation used to model steady uniform flow with a velocity (U = Q/A, m/s), in a cross-section with the hydraulic radius, R (m).

$$S_f=n^2\cdot\frac{Q\cdot|U|}{A\cdot R^{4/3}} \qquad (7)$$

By substituting Eq.(5) and Eq.(7) in Eq.(6), the momentum equation becomes as follows (Rossmann, 2017):

$$\frac{\partial Q}{\partial t}=2U\cdot\frac{\partial A}{\partial t}+U^2\cdot\frac{\partial A}{\partial x}-g\cdot A\cdot\frac{\partial H}{\partial x}-g\cdot A\cdot S_f \qquad (8)$$

Equation (8) computes the time trajectory of flow in a conduit or in a channel by using the heads provided from the continuity relationship (Eq.9) at junction nodes that connect conduits together within the node-link network.

$$\frac{\partial V}{\partial t}=\frac{\partial V}{\partial H}\cdot\frac{\partial H}{\partial t}=A_s\cdot\frac{\partial H}{\partial t}=\sum Q \qquad (9)$$

Here, V represents node assembly volume (m^3) and A_s, node assembly surface area (m^2) (Rossmann, 2017). The spatial and temporal derivatives are solved by finite difference approximations with a time step (Δt) throughout the simulation period and substituted into the link momentum equation (Eq.6). SWMM 5 uses an implicit backwards Euler method to provide improved stability (Ascher and Petzold, 1998).

The drainage routes of the surface flows and their length are determined on topographic DEM maps by using the ArcMap 10.2.2 (ESRI, 2013). The cross sections of the stream bed are defined according to the topography as irregular open channels with floodplains. The flow is assumed as gradually varied flow equations and calculated depending on the mass conservation and momentum equations with dynamic wave routing. The model of the basin, subcatchments and drainage lines defined in the SWMM are shown in Fig. 5.

2.2. Estimating Point Source Pollution Loads

Since there aren’t any large-scale industrial facilities in the area, factors creating significant environmental pressure in the basin are the agricultural and animal husbandry activities as well as household wastewaters. While the point source pollution is the urban wastewater, non-point sources include pollution loads in streets in residential areas, the fertilizers and pesticides used in agricultural and animal husbandry activities, whose the residues are discharged into Davutlar bay via the surface flow.

Therefore, the point and non-point source pollution loads drained into the bay are calculated using separate methods. The methods proposed in the project of Preparation of the Basin Protection Activity Plans (TUBITAK-MAM, 2010) are used to predict point source pollution loads. The urban wastewater flow rates from the settlements populate between 2,000 and 100,000 are calculated due to the wastewater formation values per person suggested in the Turkish Declaration of Technical Procedures of Wastewater Treatment Plant (AATTUT, 2010). Pollution loads arising from urban wastewater associated with the population living in the area based on 2017 census and the estimated population staying in the area during the high season are given in Table 2. The settlements with population less than 2,000 have been excluded from the evaluation.

The pollution load originating from residential areas is considered as point source load in settlements with sewage water system, and as distributed source in places without sewage water system. Point source urban pollution loads are discharged into the bay either directly or after being treated to a certain level depending on the presence of a wastewater treatment plant (WTP).

Table 2. Annual urban wastewater and pollution production before WTP

	Regional Population in 2017	Annual Total Wastewater Production (m^3/day)	Total COD (tons)	Total BOD (tons)	Total TSS (tons)	Total NT (tons)	Total PT (tons)
Tourism season (June-September)	500,000	50,000.00	5,475.00	3,041.67	3,041.67	425.83	66.92
Other months	38,803	3,492.27	708.15	424.89	424.89	56.65	9.44
		Annual total pollution load:	6,183.15	3,466.56	3,466.56	482.48	76.36

Pollution loads related to domestic wastewater are calculated separately before and after the Kuşadası Wastewater Treatment Plant (Kuşadası WTP) is put into operation. The Kuşadası WTP is expected to eliminate the domestic pollution load transferred to the bay to some extent. The efficiency of the plant that will operate for physical and biochemical treatment is evaluated in percentages as suggested in the project of Preparation of the Basin Protection Activity Plans (TUBITAK-MAM, 2010).

The pollutant removal efficiency in plants capable of nitrogen and phosphorus removal accepted as 80% for COD, BOD and TSS, 70% for NT, and 70% for PT. The produced load is the total load resulting from the domestic wastewaters discharged to the coastal zone. The removed load consists of the loads eliminated in WTP through adsorption or biological degradation in cesspools. The total discharged load includes the entire portion of discharges to the bay after treatment. The annual total pollution loads to be discharged to the bay after the WTP is shown in Table 3.

Table 1. Annual urban wastewater and pollution production after WTP

Parameter	Produced (tons)	Removed (tons)	Discharged (tons)
COD	6,183.15	4,946.52	1,236.63
BOD	3,466.56	2,773.25	693.31
TSS	3,466.56	2,773.25	693.31
Total N	482.49	337.74	144.75
Total P	76.36	53.45	22.91

2.3. Modelling of the Distributed Pollution Loads

The distributed pollution loads find access to the basin by mixing in surface or underground waters and drain to the bay. The SWMM v5.1 model is used in determining the flow rates of surface streams and regional distributed loads in the sub-basins surrounding the bay. The SWMM is a simulation model for surface flow hydraulics and water quality for short or long periods with dynamic wave method. It works under the Microsoft Windows operation system and performs hydrologic, hydraulic and water quality simulations for surface flows. It provides an integrated medium for changing data input and for calculation of the effects of such changes on surface flows in the basin. It defines the lands on which surface flows are formed as subcatchments. Losses arising from permeability are expressed with Horton, Green and Ampt or SCS method. Hydraulics of the surface flows on permeable or impermeable surfaces is calculated using the Manning equation (Rossman and Huber, 2015; Rossman, 2017).

Surface pollutant loads build up in the subcatchments and wash-off with the surface flow are modeled by build-up and wash-off equations based on saturation functions. The drainage routes of the surface flows and their length are determined on topographic DEM maps by using the ArcMap 10.2.2 (ESRI, 2013). The model routes are divided into fragments where major changes in the geometry of the drainage channel occur. The stream bed of the drainage lines are defined according to the topography in the SWMM model as irregular open channels with floodplains. The flow in open channels, assumed as gradually varied flow equations, is calculated depending on the mass conservation and momentum equations with dynamic wave routing. Outfall points to the bay are defined by taking the topography into consideration. The model of the basin, subcatchments and drainage lines defined in the SWMM are shown in Fig. 5.

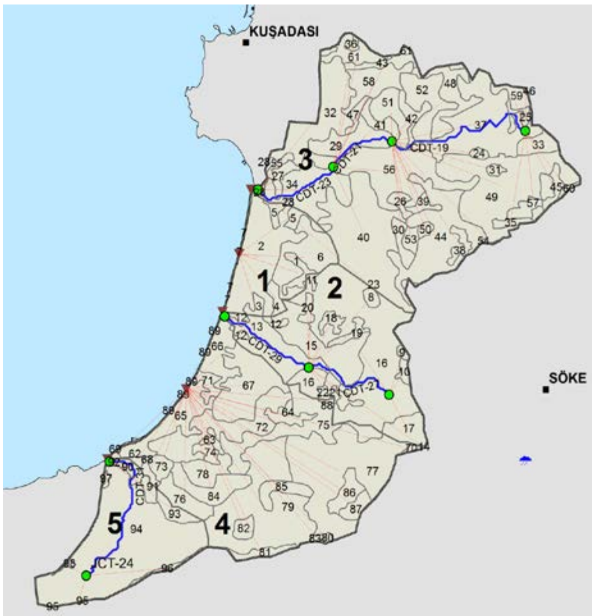

Fig. 5. Model of the basin, subcatchments and drainage lines in the SWMM

The precipitation and meteorological data of the basin are obtained from SÖKE Station of Meteorology Directorate General. The data input is of five-year averaged daily time series in the model. Hydraulic parameters of subcatchments are classified based on landuse type in the SWMM program. Landuses are divided into different classifications in the CORINE system. Hydraulic parameters of these groups are determined as estimated values according to the studies in the literature (Cebe and Balas, 2018).

The flow across the surface of SUB-BASIN-2 discharges to the sea through the Ağaçlı Brook, of SUB-BASIN-3 through Yörük Brook, and of SUB-BASIN-5 through Bal Creek. Since no surface stream appears in SUB-BASIN-1 and 4, it is accepted that the water reaches to the sea in a linear form alongside the coast. The time series of flow rates calculated by the model at outfall points of sub-basins 2, 3 and 5 are shown in Fig. 6.

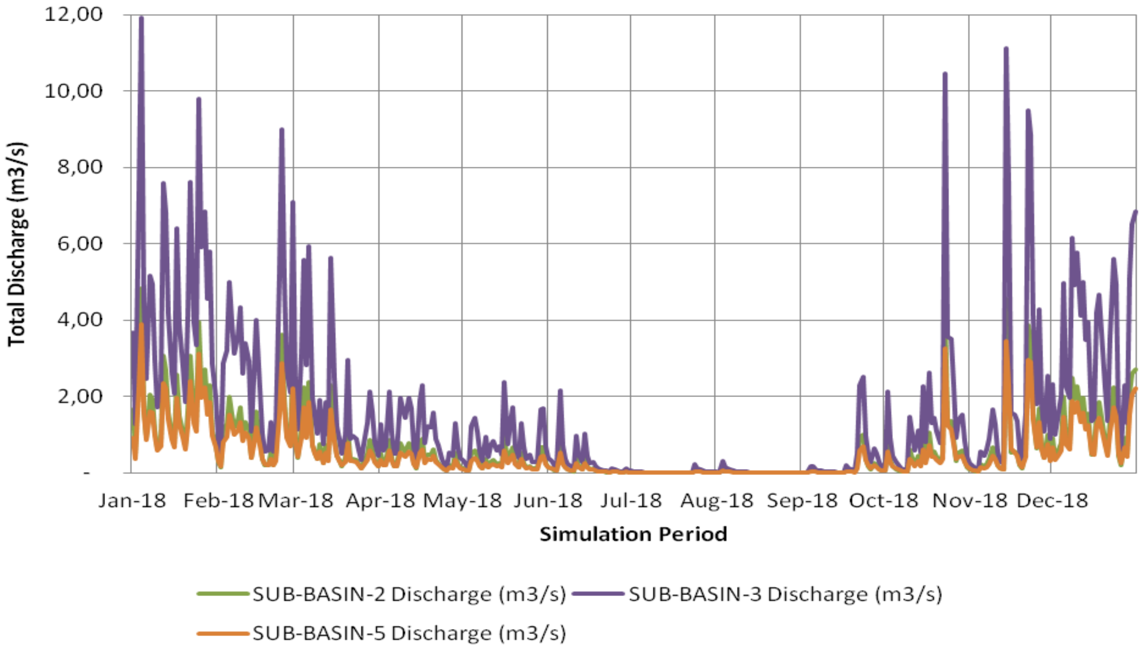

Fig. 6. Flow rates at outfall points of sub-basins 2, 3 and 5 in the SWMM model

The surface flows from the sub-basins and the maximum and mean flow rates are summarized in Table 4. Formation of distributed pollution loads on the land and the process of transport through surface flows are calculated with build-up and wash-off processes in the model. The build-up process calculates the mass of pollutants in the subcatchments depending on the type of landuse. This process can be expressed as the mass of the pollutant emerged in the unit area of the subcatchment according to a build-up curve. The build-up amount is a function of the number of sequential days without precipitation. The transport of pollutants in the subcatchments via surface waters through erosion and their dissolution after precipitation is called as wash-off mechanism. The amount of pollutants transported to the coastal area in this process is calculated as a function of mean concentration in the SWMM model (Gironás et al., 2009). In this project, it is accepted that the maximum pollutant concentration in the surface flows remains constant throughout each precipitation.

Table 4. Estimated annual surface flow

AREA	Average Flow (m^3/s)	Maximum Flow (m^3/s)	Total Volume (10^6 m^3)
SUB-BASIN-1	-	-	38.995
SUB-BASIN-2	2.414	67.724	75.277
SUB-BASIN-3	6.252	176.517	197.286
SUB-BASIN-4	-	-	140.385
SUB-BASIN-5	1.349	31.855	42.238

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In this project, it is accepted that the maximum pollutant concentration in the surface flows remains constant throughout each precipitation.

The pollutant concentrations in surface flows in each sub-basin are simulated by the SWMM model using the five year averaged daily precipitation data for a period of 365 days. The estimated pollutant concentrations discharged to the bay from SUB-BASINS 2, 3 and 5 are shown in Fig. 7.

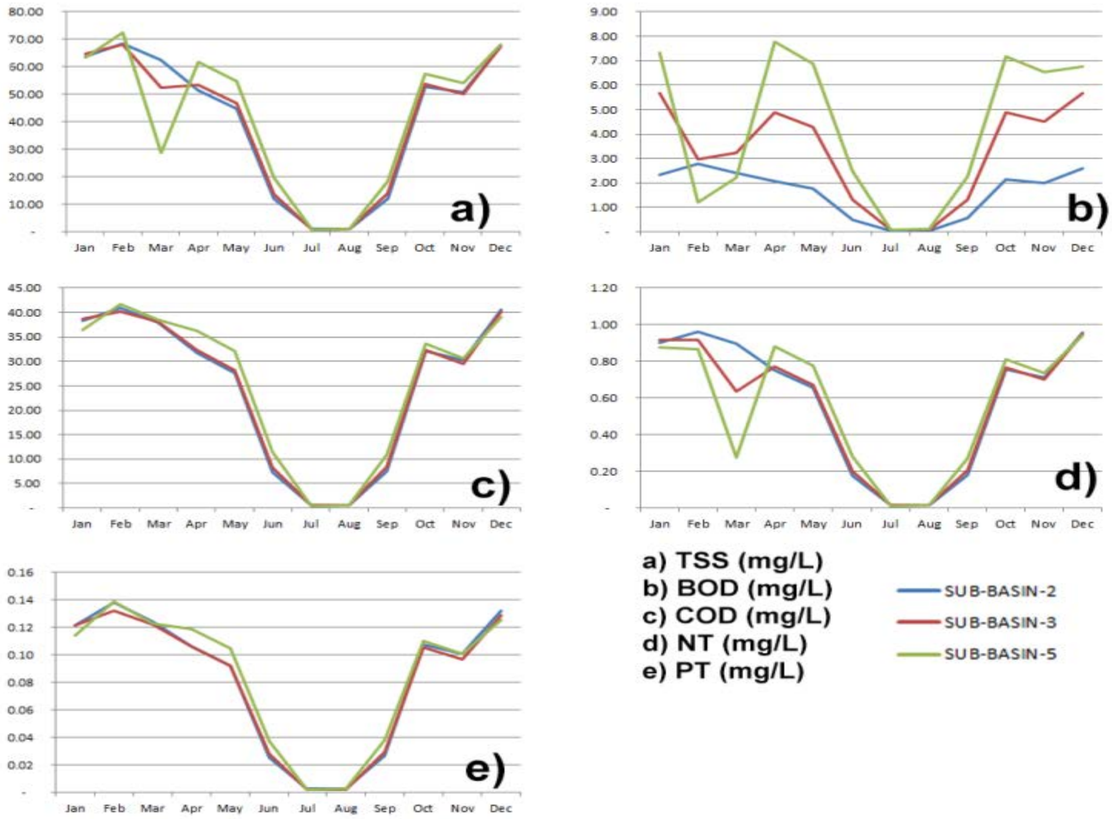

Fig. 7. Estimated pollutant concentrations of surface streams

Since no precipitation is recorded during the summer months, periods without surface flows appear in the simulation. During such periods pollutants accumulate on the land. They drain into the sea upon precipitations in the autumn. The winter and spring seasons yield high rates of surface flows resulting in high concentration rates of pollutants. Annual total discharge amount of pollutants reaching the bay through surface flows are shown in Table 5.

Table 5. Annual total pollutant loads drained through surface flows

Area	Total TSS (tons)	Total BOD (tons)	Total COD (tons)	Total NT (tons)	Total PT (tons)
SUB-BASIN-1	2,698.053	11.912	1,564.251	37.486	4.768
SUB-BASIN-2	5,199.359	214.608	3,123.101	73.828	10.079
SUB-BASIN-3	13,542.724	1,025.440	8,304.618	190.980	26.746
SUB-BASIN-4	9,610.602	689.076	5,775.017	133.756	19.260
SUB-BASIN-5	2,807.943	279.447	1,716.966	37.776	5.618
TOTAL	33,858.681	2,220.483	20,483.953	473.828	66.472

Annual total pollution loads drained into Davutlar bay before and after WTP are summarized in Table 6.

Table 6. Change in the annual pollutant loads discharged into the sea after WTP

	Total COD (tons)	Total BOD (tons)	Total TSS (tons)	Total NT (tons)	Total PT (tons)
Before wtp	26,667.11	5,687.04	37,325.24	956.31	142.83
After wtp	21,720.58	2,913.79	34,551.99	618.57	89.38
Reduction (%)	18.55%	48.76%	7.43%	35.32%	37.42%

3. CONCLUSION

Model results demonstrate that the pollution loads build up in the basin are higher than those of the urban wastewater. Since the pollutants that reach the bay are mostly distributed loads and the WTP is effective on point source loads, only a limited reduction in total pollutant loads is expected after the WTP is put into operation. From the model results we obtain that the reduction in pollutants discharged into the sea will remain within the range of 7.43% and 48.76%. After the WTP, the maximum change is seen in BOD discharge with a percentage of 48.76. Reductions in NT and PT discharge are expected to be 37.42% and 35.32%, respectively. The amount of TSS mostly originates from surrounding basins and is drained to the bay with surface waters. WTP is expected to reduce only 7.43% of the TSS load.

Putting the WTP into operation will, in the short term, be significantly effective on the reduction of pollutant loads discharged to Davutlar bay in relation to the dense population particularly in the high season. Reduction of pollutants arising from agricultural and animal husbandry activities, however, requires extra measures. In order to control the pollutants transported to the sea via surface flows, best management practices should be implemented, such as terracing, settling tanks, employing simple treatment systems, forming green bands on drainage lines, and removal of pollutant loads in the land.

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