

HYDROTAM: 3D Model for Hydrodynamic and Transport Processes in Coastal Waters

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Abstract: HYDROTAM is a Geographic Information Systems (GIS) integrated three-dimensional baroclinic numerical model that has been developed to simulate the hydrodynamic and transport processes in coastal waters. The infrastructure of the program is based on cloud computing technology. GIS platform of HYDROTAM facilitates the time consuming task of preparation of data input and output. On the model interface, all functions of the MS Silverlight framework are available to the user with a menu driven graphical user interface (GUI). The numerical model consists of hydrodynamic, transport, turbulence and wave propagation model components. In the hydrodynamic model component, the 3D Navier–Stokes equations are solved with the Boussinesq approximation. The transport model component consists of the pollutant transport, water temperature and salinity transport and suspended sediment transport models. In the turbulence model, a two-equation k – ϵ formulation is solved to calculate the kinetic energy of the turbulence and its rate of dissipation, which provides the variable vertical turbulent eddy viscosity. In wave propagation component, mild slope equations are solved.

Keywords: GIS; modelling; cloud computing; coastal waters; hydrodynamics

1. INTRODUCTION

HYDROTAM is an unsteady three-dimensional baroclinic circulation model that has been developed to simulate the transport processes in coastal water bodies (Balas and Özhan, 2000). It has hydrodynamic, transport, turbulence and wave model components. The model computes the full spatial distribution of velocities of unsteady flow induced by wind, tide or water density differences solving full Navier–Stokes equations with only Boussinesq approximation. The transport model component consists of the pollutant transport model, the water temperature and salinity transport models and the suspended matter transport. The numerical model includes thermohaline forcing due to changes in the sea water density. The density of sea water is a function of its salt content, its temperature and to a much lesser degree, its pressure. The two equation k – ϵ turbulence model is used for the turbulence modelling (Balas and Özhan, 2001). To consider the large scale turbulence caused by the horizontal shear, horizontal eddy viscosity is simulated by the Smagorinsky algebraic subgrid scale turbulence model (Balas and Özhan, 2000). The pollutant transport model can simulate the near and far field dilutions of sea outfalls. Pollutant may or may not decay. The rate of disappearance of pathogenic bacteria and viruses due to die-off approximately follows the first order kinetics. The die off constant k_p , is computed in terms of T_{90} , the time required for 90 percent of the

initial bacteria to die (Balas, 2001). The suspended sediment transport model simulates the advective and diffusive transport, settling, deposition and re-suspension of suspended matters. In coastal waters erosional and depositional areas can be identified.

HYDROTAM, integrated with GIS (<http://hydrotam.com>), computes the wind and wave climate analyses of Turkish coast line. Most of the Turkish coastline and the Turkish Bays' bathymetries are provided on GIS mapping. Wind and wave roses based on over 40 years of meteorological data(1970-2011) are also provided for all the Turkish coastal meteorological stations. Upon selection of the coastal location, the user can investigate the current pattern or the transport mechanisms with nearest meteorological stations wind and wave rose data.

Based on the predicted deep water wave height, its propagation to the coast line is numerically simulated by using the modified mild slope equations. Model equations govern combined effects of shoaling, refraction, diffraction, reflection and breaking. Nonlinear and irrotational waves are considered, and the effects of currents on the wave propagation are assumed to be negligible. It is assumed that energy propagates along the wave crests, however, the wave phase function changes to handle any horizontal variation in the wave height. Model does not have the limitation that one coordinate should follow the dominant wave direction. Different wave approach angles can be investigated on the same computational grid (Balas and İnan, 2001; İnan and Balas, 2006,2008)

Solution scheme is a composite finite element-finite difference scheme (Balas and Özhan, 2000). The governing equations are solved by Galerkin Weighted Residual Method in the vertical plane and by finite difference approximations in the horizontal plane, without any coordinate transformation. The water depths are divided into the same number of layers following the bottom topography. So, the vertical layer thickness is proportional to the local water depth. The model predictions were verified by using several experimental and analytical results published in the literature and its successful use for a variety of real life cases was demonstrated (Balas and Özhan, 2002).

2. HYDROTAM MODEL COMPONENTS

The basic model components of HYDROTAM are summarized in the Figure 1. The advantages of the model can be listed as;

1. It is a three-dimensional coastal numerical model, following the bottom topography. It uses variable mesh sizes in horizontal and vertical planes.
2. It uses cloud computing architecture and it does not need any hardware, software investment and does not require system maintenance/management.
3. It provides an economical solution, i.e. pay only for your needed use.
4. It is fast as it uses multi-core computing environment.
5. In its interface all functions of the MS Silverlight framework are available to the user in a menu driven graphical user interface (GUI).
6. Geographic information system(GIS) based outputs of the model is easily interpretable and understandable.
7. The model uses a global coordinate system.
8. It uses finite elements and finite difference methods.
9. It provides unsteady solutions, i.e results for any period of time specified by the user.
10. Model is baroclinic, i.e. it can handle water temperature, salinity and density variations as well as barotropic pressure gradients.

11. Turkish coastline and most of the Turkish Bay bathymetries are provided on GIS mapping. Wind and wave roses based on over 40 years data (1970-2011) are also provided based on all the Turkish Coastal Meteorological Stations.
12. It provides yearly or seasonal wind and wave roses.
13. Model allows the installation of any bathymetrical data to the system.
14. Model can be applied coastal marine, estuarine, lagoon and lake environments

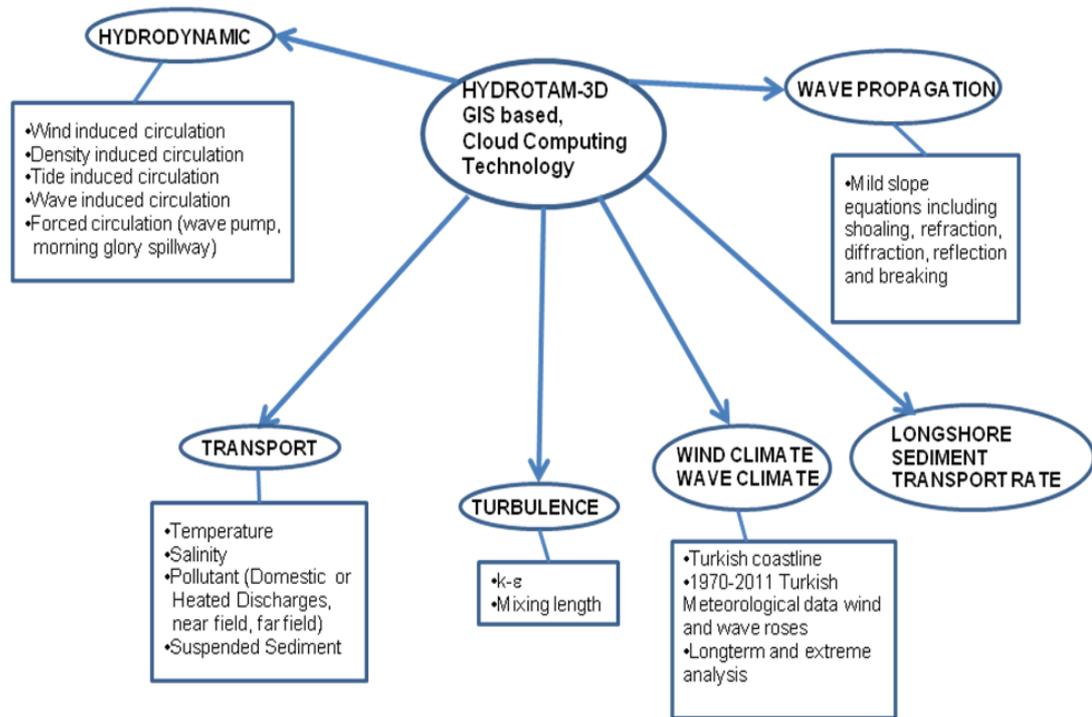


Figure 1. Basic model components of HYDROTAM

3. THEORY

Enclosed or semi-enclosed coastal areas have limited water exchange. Therefore, to understand water circulations and transport processes is a delicate matter. Since field measurements are usually costly and sometimes impossible due to physical inabilities, application of numerical models becomes more and more important in the simulations of coastal water processes. Use of three-dimensional models is unavoidable in all cases where the influence of density distribution or the vertical velocity variations cannot be neglected and in the simulation of wind induced circulation (Balas, 2001).

The governing model equations of HYDROTAM in the three dimensional Cartesian coordinate system are as follows (Figure 2):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = fv - \frac{1}{\rho_0} \frac{\partial p}{\partial x} + 2 \frac{\partial}{\partial x} (v_x \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y} (v_y (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})) + \frac{\partial}{\partial z} (v_z \frac{\partial u}{\partial z}) \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -fu - \frac{1}{\rho_0} \frac{\partial p}{\partial y} + 2 \frac{\partial}{\partial y} (v_y \frac{\partial v}{\partial y}) + \frac{\partial}{\partial x} (v_x (\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y})) + \frac{\partial}{\partial z} (v_z \frac{\partial v}{\partial z}) \quad (3)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho_0} \frac{\partial p}{\partial z} - g + \frac{\partial}{\partial y} (v_y (\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z})) + \frac{\partial}{\partial x} (v_x (\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z})) + \frac{\partial}{\partial z} (v_z \frac{\partial w}{\partial z}) \quad (4)$$

where, x, y : Horizontal coordinates; z : Vertical coordinate; t : Time; u, v, w : Velocity components in x, y, z directions at any grid locations in space; v_x, v_y, v_z : Eddy viscosity coefficients in x, y and z directions, respectively; f : Coriolis coefficient; $\rho(x, y, z, t)$: In situ water density; ρ_0 : Reference density; g : Gravitational acceleration; p : Pressure.

The numerical model includes thermohaline forcing. Temperature and salinity variations are calculated by solving the three dimensional convection-diffusion equation which is written as:

$$\frac{\partial Q}{\partial t} + u \frac{\partial Q}{\partial x} + v \frac{\partial Q}{\partial y} + w \frac{\partial Q}{\partial z} = \frac{\partial}{\partial x} (D_x \frac{\partial Q}{\partial x}) + \frac{\partial}{\partial y} (D_y \frac{\partial Q}{\partial y}) + \frac{\partial}{\partial z} (D_z \frac{\partial Q}{\partial z}) \quad (5)$$

where, D_x, D_y and D_z : Turbulent diffusion coefficient in x, y and z directions respectively; Q : Temperature (T) or salinity (S).

The three dimensional conservation equation for suspended sediment where the vertical advection includes the particle settling velocity can be written as:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} + w \frac{\partial C}{\partial z} - w_s \frac{\partial C}{\partial z} = \frac{\partial}{\partial x} (D_x \frac{\partial C}{\partial x}) + \frac{\partial}{\partial y} (D_y \frac{\partial C}{\partial y}) + \frac{\partial}{\partial z} (D_z \frac{\partial C}{\partial z}) \quad (6)$$

where C : Suspended sediment concentration; w_s : Settling velocity.

The two equation $k-\epsilon$ turbulence model is used for the turbulence modelling [6],[7]. To consider the large scale turbulence caused by the horizontal shear, horizontal eddy viscosity is simulated by the Smagorinsky algebraic subgrid scale turbulence model:

$$\nu_h = 0.01 \Delta x \Delta y \left(\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + \frac{1}{2} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 \right)^{1/2} \quad (7)$$

Horizontal eddy diffusivities are approximately equal to the horizontal eddy viscosities. On the other hand, the vertical diffusivity, D_z , is expressed as:

$$D_z = \frac{\nu_z}{Pr} \quad (8)$$

where, Pr is the turbulent Prandtl or Schmidt number and ν_z is the vertical eddy viscosity coefficient.

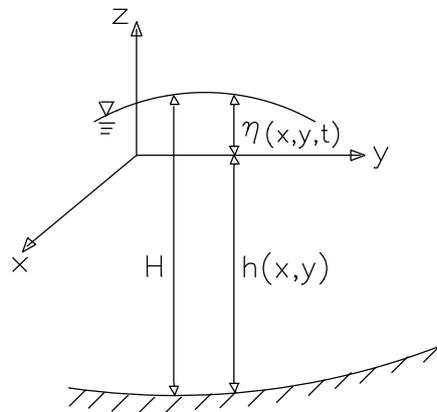


Figure 2. Definition sketch for the water surface elevation and water depth.

As the turbulence model k-ε model is used. The standard k-ε model assumes the local isotropy of the turbulence, where horizontal eddy viscosity is equal to the vertical eddy viscosity. If the horizontal motion has an intensity and length scale greater than the vertical motion, like in shallow water bodies, the standard, single length scale, k-ε turbulence model underestimates the effective horizontal eddy viscosities. To account for large scale turbulence generated by the horizontal shear, horizontal eddy viscosity is simulated by the Smagorinsky algebraic subgrid scale turbulence model. The two equation k-ε turbulence model is used for turbulence modelling. Water density is considered as a variable depending on water salinity and temperature. Wave propagation is numerically solved by modified mild slope equation (Inan and Balas, 2009); Wave driven current model is based on the solution of vertically averaged non-linear shallow water equations that include nonlinear convective accelerations, lateral mixing and bottom friction. Longshore sediment transport rate is calculated by the CERC Formula based on the longterm wave statistics. As the longterm wave statistics, log-normal analyses has been applied.

4. APPLICATIONS OF HYDROTAM

Cloud computing structure of the model HYDROTAM is presented in Figure 3.

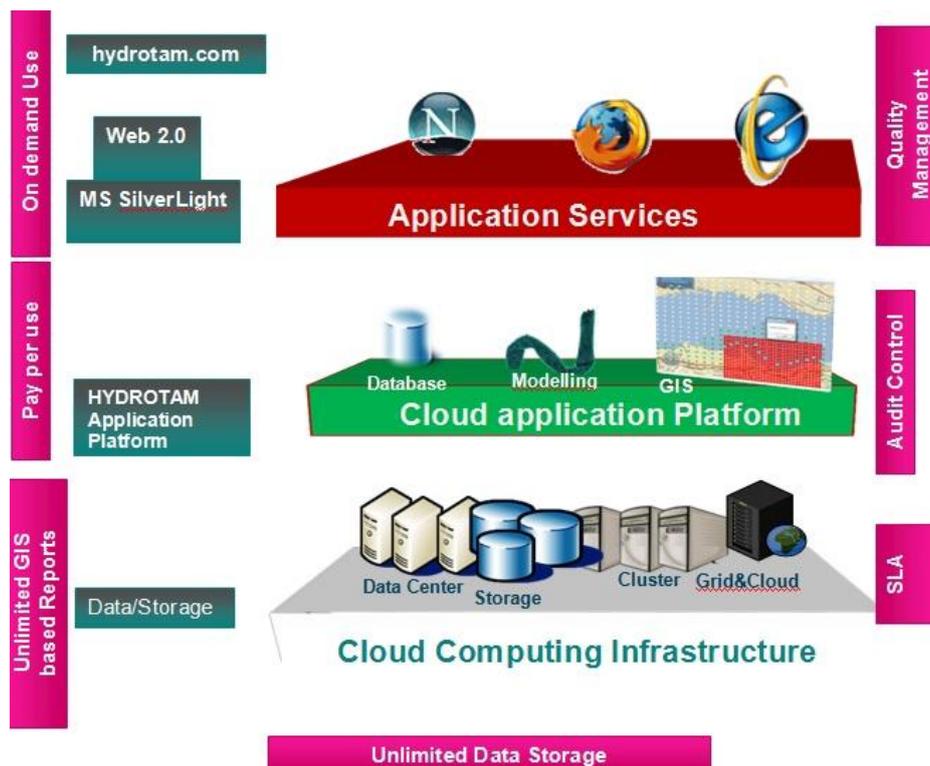


Figure 3. HYDROTAM Cloud Computing Structure

The project area is selected and a mesh system is fitted on the MAP (Figure 4). Green mesh points are land points, yellow mesh points are sea-land boundaries, and blue mesh points are points in the sea water. Using the change tool, user can change the type of the mesh point after it is created by the model. Light blue points are freely chosen by the user. User can mark as many light blue points as

she/he wishes on the mesh system created. These points are the coordinates where the user wants to see pointwise detailed information about the water column from the surface up to the bottom of the sea.

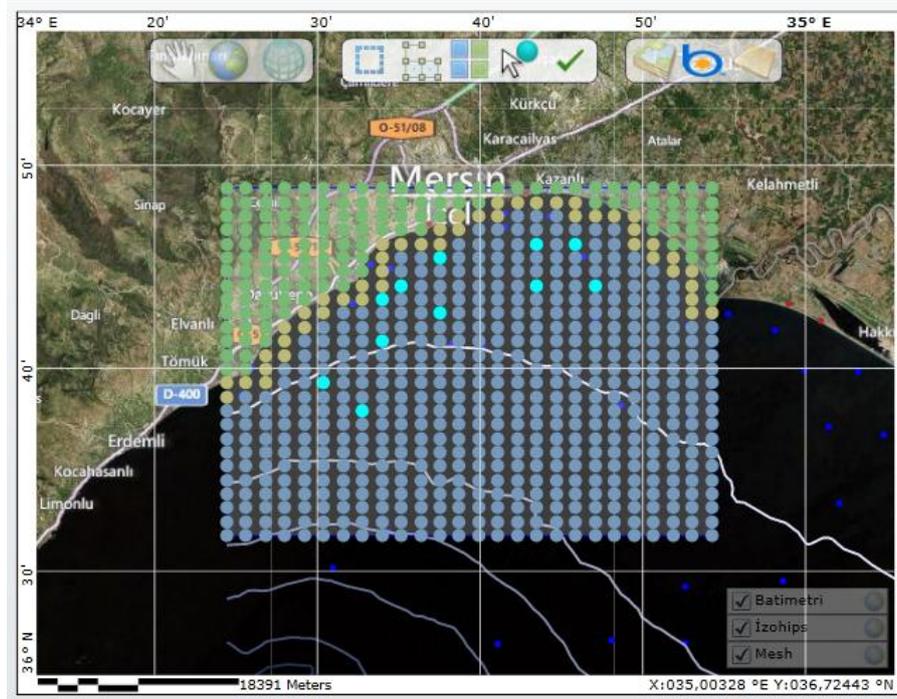


Figure 4. Mesh generation by the model

The modeled quantity under concern (current velocity, pollutant concentration, salinity, temperature, sediment, wave height etc.) is plotted and animated in time on the map provided. It is possible to export all images (Figure 5).

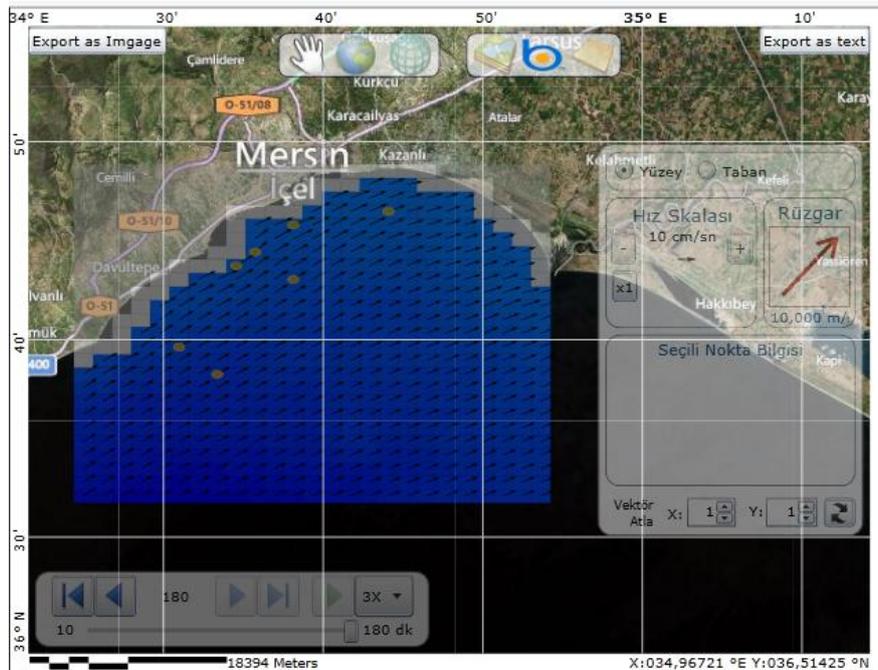


Figure 5. Animation of the modelled quantities (current velocity)

The vertical change of modeled quantity under concern through the water depth can be animated time wise and it is possible to export the animation (Figure 6). By the rotation tool shown on the left corner, it is possible to change the angle of the view freely by the user.

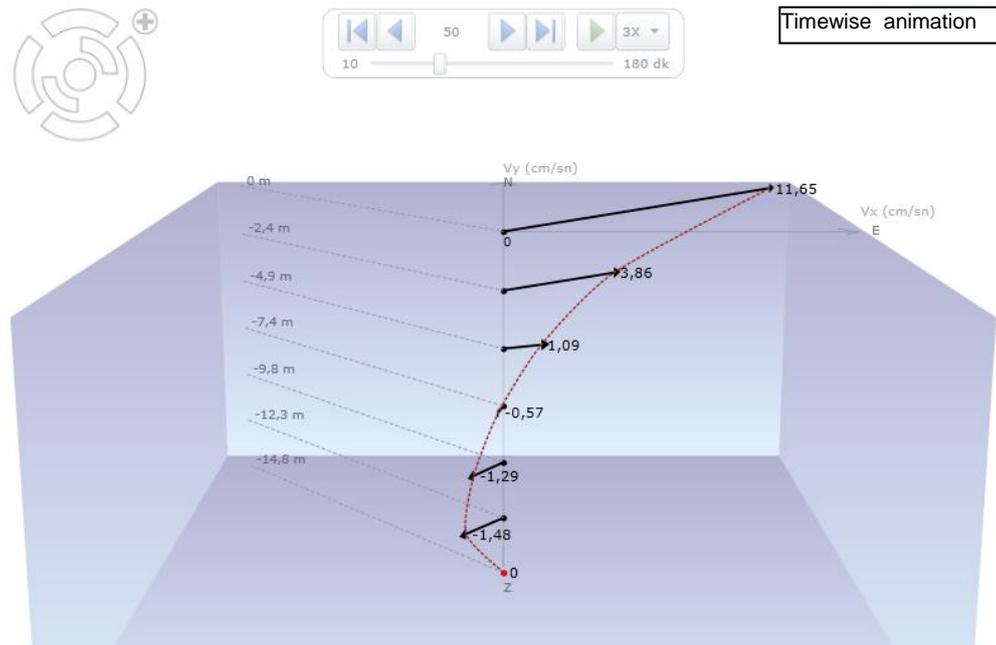


Figure 6. Timewise animation of the modelled quantity for the selected mesh point.

In the wave and wind climate sub model (Figure 7), user can select the point of concern on the map (yellow point). After the point selection, fetches (distances from land to land in all principle directions) are created automatically by the model based on GIS. User can change the length of the fetch if needed by using the change tool on the left. Then user selects the nearest meteorological station data for the analyses.

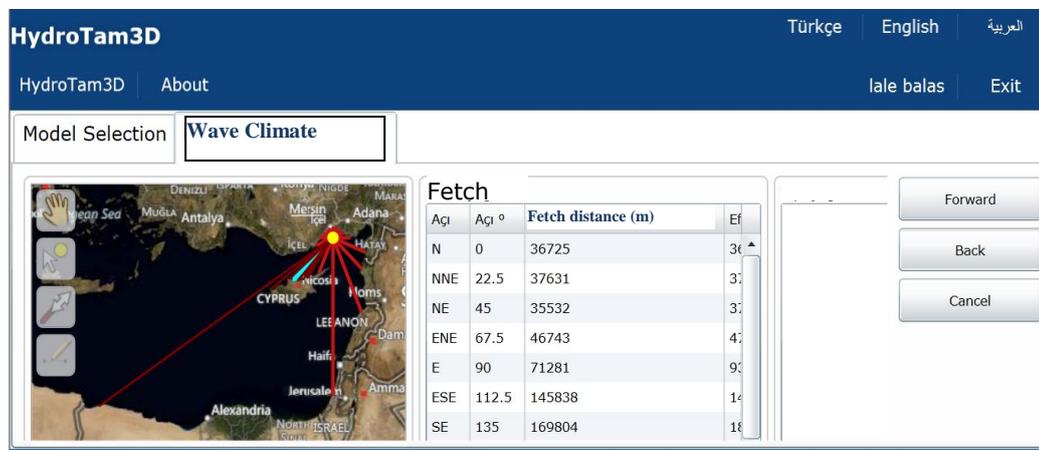


Figure 7. Fetch calculation for wave climate

5. CONCLUSIONS

HYDROTAM is a Geographic Information Systems (GIS) integrated three-dimensional baroclinic numerical model that has been developed to simulate the hydrodynamic and transport processes in coastal waters. The GIS platform facilitates the time consuming task of preparation of data input and output structures. In its interface, all functions of the MS Silverlight framework are available to the user in a menu driven graphical user interface (GUI). Cloud computing describes a new supplement, consumption, and delivery model for IT services based on the Internet, and it typically involves over-the-Internet provision of HYDROTAM. Therefore, HYDROTAM model takes all the form of web-based tools or applications that users can access and use through a web browser as if it were a program installed locally on their own computer. In a cloud, all required HYDROTAM software (operating system, database, GIS tools, business or scientific applications, etc.) reside on a service providers server external to a user's computer. Cloud computing requires less power because a lot of the processing overhead is performed at a server and not at a personal computer. Consequently, the need for extremely powerful computers is not required and CPU time is significantly reduced. HYDROTAM Cloud computing is a platform allowing IT hardware and software runs on the Internet for coastal and environmental problems (<http://www.hydrotam3d.com>). Cloud computing is an internet-based computing, and whereby shared resources, software, and information are provided to computers and other devices on demand. HYDROTAM use would be a subscription based or pay as you go model.

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