# Manual for Software Package to Run Henry Problem with Pumping for Heterogeneous Hydraulic Conductivity Fields

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The user has to install FloPy (version 3.3.3 or newer) and Numpy (1.19.2 or newer) to run the software packages. Executable file of SEAWAT (swt_v4.exe) should also be put in the same directory.

There are two main programs in the repository:

1) HenryLarge_Hetero_HR_Real_Sample_Pump_LPR_10extraReals.py

with input file: hk_init86p4_1_5range_10reals_new.npy (10 realizations of heterogeneous hydraulic conductivity fields with the same geostatistic parameters, i.e., mean, variance, and variogram)

2) HenryLarge_Hetero_HR_Real_Sample_Pump_LPR_10reals.py

with input file: hk_init86p4_1_5range_10reals.npy (10 extra realizations of heterogeneous hydraulic conductivity fields with the same geostatistic parameters, i.e., mean, variance, and variogram)

There is also a post-processing file written in Matlab to generate response curves for three different state variables (toe positions of the salt water wedge, concentration at the well, and the total dissolved solute in the aquifer):

HenryHeteroLarge_SV_LPR_10plus10reals.m

A brief discussion of the problem set for the software package is described as follows:

## Henry's Problem with One Central Pumping Well

As one of the classic seawater intrusion problem set-up, Henry's problem (Henry, 1964) has been widely benchmarked and modified for further analysis (e.g., Javadi et al., 2012; other references). We adopted the original model set up from Henry (1964) in our investigation by enlarging the model domain to a quasi-2D domain with a dimension of 200-m long by 100-m deep by 1-m wide (into the page) (similar to the model dimension used in Javadi et al., 2011), and adding one single pumping well located in the central part of the aquifer (Fig. 1).

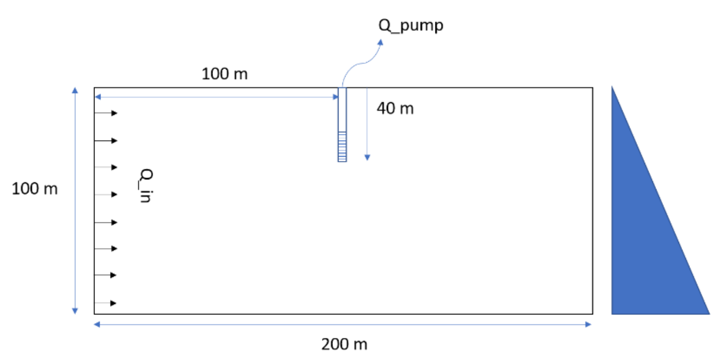


**Figure 1**. Schematic domain of the modified Henry's problem

We developed a variable density groundwater model using SEAWAT that couples fluid flow and solute transport to conduct our analysis. The numerical model is discretized into 100 columns and 50 rows, with each cell having a dimension of 2m by 2m. The landward recharge is represented by a constant (1140.4 $m^3$/day) fresh water influx coming from the left side boundary. The coastal boundary is represented by a constant seawater head boundary for groundwater flow and point source (35g/L) boundary for the solute transport. The top and bottom boundaries are no-flux boundaries for both flow and transport. We neglected the velocity-dependent dispersivity, but took into account the molecular diffusion and the coefficient is set to be 1.62925 $m^2$/day. A complete list of parameters used in the numerical experiment is shown in Table 1.

Table 1.

| **Parameter Name** | **Value** |
|---|---|
| Lx: domain Length (m) | 200 |
| Lz: domain depth (m) | 100 |
| alpha_T: transverse dispersivity (m) | 0 |
| alpha_L: longitudinal dispersivity (m) | 0 |
| Dm: molecular diffusion coefficient ($m^2$/day) | 1.62925 |
| Qin: inland fresh water flux ($m^3$/day) | 1140.4 |
| Rho_w: density of fresh water (kg/$m^3$) | 1000 |
| Rho_s: density of sea water (kg/$m^3$) | 1025 |
| K: hydraulic conductivity (m/day) | Varying, see text |
| Qwell: pumping rate (normalized w.r.t. Qin) | 0,1,2,3,4,5 |

The initial condition of the model is saturated with seawater (35g/L) at a hydrostatic condition. There are two stress periods of the simulation with each period lasting for 30 days. In the first period, we let the freshwater coming from the left to flush some of the seawater out of the system from the top right outlet of the domain (30 days, 15 time steps). After the seawater wedge and the fresh water flux reached a quasi-steady-state equilibrium, we started the second period by turning on the central well to extract water out of the system and let the pumping continue for another 30 days. At the end of the simulation, the system reached new steady-state after readjusting to the pumping disturbance.

To address the uncertainty associated with hydraulic conductivity in the field, one of the key parameters that are expensive to characterize but play critical roles in determining both the flow field and transport processes, we conducted a series of sensitivity analysis for 1) homogeneous cases, 2) cases with layered hydraulic conductivity, 3) heterogeneous cases with different correlation lengths and reference log-normal distributions (mu, sigma^2) for the random fields. To quantify the seawater intrusion extent and the quality of the pumped water, we chose 1) the toe position of the seawater front along the bottom, 2) the concentration at the pumping well, and 3) the total dissolved mass in the aquifer as three state variables (SV) and chose the pumping rate as the single decision variable (DV) to construct the response surfaces.