Sensitivity Analysis of SWAT Using SENSAN

Zhulu Lin
Department of Agricultural and Biosystems Engineering
North Dakota State University at Fargo
zhulu.lin@ndsu.edu

Model sensitivity analysis can help us assess the relative sensitivity of model output with respect to the changing of model parameters. It often is the first step in a model calibration exercise whereby key model parameters can be identified. This note briefly illustrates how to utilize SENSAN (a PEST companion program) and MS Excel to conduct sensitivity analysis for the SWAT model. SENSAN adopts a local sensitivity analysis method which takes a one-at-a-time (OAT) approach. In this approach, the impact of changing values of each model parameter on the model outputs is evaluated one at a time. That is, model output responses are determined by sequentially varying each of the model parameters and by fixing all other parameters to their nominal values. Often these nominal values are taken from literature. The combination of nominal values for all the model parameters under inspection is called the "control" scenario. While the low computational cost is one of the main advantages of the OAT approach, the OAT method has many limitations when applied to complex (nonlinear) environmental models such as SWAT. One limitation of the OAT methods is that they do not account for any interaction between model parameters (if any exists) since the sensitivity analysis is performed for one parameter at a time by fixing all other parameter at constant nominal values. Furthermore, in a local method, parameters are changed over small intervals around their nominal values. These nominal values represent a specific point of the parameter space (i.e., the "control" scenario). Results of such a local method are thus dependent on the choice of this point, and the model behavior is identified only locally in the parameter space (namely, around the selected point). The farther the perturbation in parameter moves away from the nominal value, the less reliable the analysis results will be. It is acceptable only if the input-output relationship can be adequately approximated through a first-order polynomial (i.e., linear input-output relationship). However, if the model shows strong nonlinearity (like many hydrologic and water quality models) between model parameters and model outputs then a change in the selected nominal values ("control" scenario) will provide totally different sensitivity results. Therefore, care should be exercised when interpreting the sensitivity analysis results from the SENSAN program.

1. SENSAN Files

1.1 SENSAN control file

Like the PEST program, SENSAN's master file is the SENSAN control file with a file extension name .sns (see Example 1). A SENSAN control file must begin with `scf` as its first line (Line 1). The remaining SENSAN control file consists of 4 blocks; each block begins with a narrative line. As in the PEST control file, each narrative line consists of an asterisk followed by a space and the block name. The block names have to be the same as those shown in Example 1. They are "`control data`", "`sensan files`", "`model command line`", and "`model input/output`". In block "`control data`", don't worry about `noverbose` (Line 3). In Line 4, the first number (`10`) is the total number of model parameters, with respect to which, the sensitivity of the model's outputs will be analyzed; while the second number (`5`) is the total number of model outputs. In Line 5, the first entity (`1`) is the number of template and input file pairs; while the second entity (`1`) is the number of instruction and output file pairs. The two ones (1's) correspond to Lines 14 and 15, respectively. Since we use the SWAT linkage interface developed by Jing Yang in the Swiss Federal Institute for Environmental Science and Technology (see "Running SWAT in A Breeze" for details on how to use the linkage interface) to run SWAT, only one pair of template and model input files is needed. All the model output variables (such as surface runoff, total water yield, sediment yield, and phosphorus loads) are read from the `output.std` file in this example, so only one pair of instruction and model output files is needed, as well. Don't worry about the entities in C3 and C4 in Line 5.

```
Ln          C1                      C2              C3        C4
1    scf
2    * control data
3    noverbose
4    10                   5
5    1                    1                         single    point
6    * sensan files
7    senpar.txt
8    senabs.txt
9    senrel.txt
10   sensen.txt
11   * model command line
12   modelswatsen
13   * model input/output
14   sens_example.tpl    sens_example.in
15   outputstd.ins       output.std
```

Example 1. A SENSAN control file

In the second block ("`sensan files`"), there are four files. The first file (Line 7) is the parameter variation file (see Example 5). Its structure will be detailed in Subsection 1.2. The rest of three files (Lines 8-10) are the output files from SENSAN, explanation of which will be given in Subsection 1.3. The third block ("`model command line`") contains only one line (Line 12) which is the name of the model batch file. See Example

2. The last block ("`model input/output`") contains the pair(s) of template-input file and pair(s) of instruction-output file. A typical template file is given in Example 3; while the instruction file for reading `output.std` file is given in Example 4. Details about model batch file, template and instruction files are given in another note entitled "Getting Started with PEST".

```
@ echo off
sw_edit > nul
swat2000 > nul
```

Example 2. The model batch file

```
ptf $
v__SURLAG.bsn            $surlag  $
v__CN2.mgt               $cn2f $
v__ESCO.hru              $esco    $
v__ALPHA_BF.gw           $alpha_bf $
v__SLOPE.hru             $slope   $
v__SPEXP.bsn             $spexp   $
v__PHOSKD.bsn            $phoskd  $
v__PSP.bsn               $psp     $
v__SOL_SOLP.chm          $sol_solp $
v__SOL_ORGP.chm          $sol_orgp $
```

Example 3. A typical template file when using the SWAT linkage interface

```
pif $
$AVE ANNUAL BASIN VALUES$
l6 $=$ !runoff!
l7 $=$ !wtryld!
l5 $=$ !sedyld!
$NUTRIENTS$
l2 $=$ !orgpyld!
l3 $=$ !solpyld!
```

Example 4. A typical instruction file for reading output.std

1.2 Parameter variation file

SENSAN's task is to run a model as many times as a user requires, providing the model with a user-specified set of parameter values on each occasion. The parameters which are to be varied from model run to model run are identified on one or a number of template files. The values which these parameters must take on successive model runs are provided to SENSAN in a "parameter variation file", an example of which is presented in Example 5.

The file shown in Example 5 provides 11 sets of values for 10 SWAT parameters; the parameter names appear in Line 1. The same parameter names must be cited on template file(s) provided to SENSAN. The second line (Line 2) contains the nominal value for each parameter, that is, the "control" scenario. In the third line, the value for parameter

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`SURLAGE` increases by 5% while the rest 9 parameters remain constant at their nominal values. In the fourth line, the value for parameter `CN2F` increases (or decreases) by 5% while the remaining 9 parameters (including `SURLAG`) take their nominal values, and so forth. A separate SWAT run will be undertaken for each row. The results, printed in the `output.std` file for each SWAT run, will be read through the instruction file (Example 4) by SENSAN, which will conduct some simple calculations and export these results to the three SENSAN output files (see Lines 8-10 in Example 1).

```
1    SURLAG   CN2F    ESCO    ALPHA_BF   SLOPE   SPEXP   PHOSKD   PSP    SOL_SOLP   SOL_ORGP
2     4        73     0.95     0.021      0.1     1.5      90     0.24      15         125
3     4.2      73     0.95     0.021      0.1     1.5      90     0.24      15         125
4     4       76.65   0.95     0.021      0.1     1.5      90     0.24      15         125
5     4        73     0.9975   0.021      0.1     1.5      90     0.24      15         125
6     4        73     0.95     0.02205    0.1     1.5      90     0.24      15         125
7     4        73     0.95     0.021     0.105    1.5      90     0.24      15         125
8     4        73     0.95     0.021      0.1    1.575     90     0.24      15         125
9     4        73     0.95     0.021      0.1     1.5     94.5    0.24      15         125
10    4        73     0.95     0.021      0.1     1.5      90     0.252     15         125
11    4        73     0.95     0.021      0.1     1.5      90     0.24     15.75       125
12    4        73     0.95     0.021      0.1     1.5      90     0.24      15        131.25
```

Example 5. A parameter variation file (The numbers in the most left column are line labels; they are not contained in the real file)

1.3 SENSAN output files

SENSAN produces three output files (named "`senabs.txt`", "`senrel.txt`", and "`sensen.txt`"), each of which is easily imported into a spreadsheet for subsequent analysis. In each of these files the first 10 (or the number of varying parameters) columns contain the parameter values supplied to SENSAN in the parameter variation file. The subsequent 5 (or the number of model output variables of interest) columns pertain to the 5 model output variables cited in the instruction file supplied to SENSAN. The first row of each of these output files contains parameter and observation names.

These three files differ from each other only by the values provided (calculated) in the last 5 columns for the model output variables. The last 5 entries on each line of the first output file (`senabs.txt`) simply list the 5 model outputs read from the model output file (`output.std`) after the model was run using the parameter values supplied as the first 10 entries of the same line. An example of the senabs.txt file is presented in Example 6. The first three columns (C1-C3) are (omitted) parameter values while the last 5 columns (C4-C8) are values for surface runoff (`RUNOFF`), total water yield (`WTRYLD`), sediment yield (`SEDYLD`), organic P yield (`ORGPYLD`), and soluble P yield (`SOLPYLD`).

The second SENSAN output file (`senrel.txt`) lists the relative difference between model output values on second and subsequent data lines of the first output file (`senabs.txt`) and model output values cited on the first data line. We don't need this

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file in our subsequent calculation of the Normalized Sensitivity Coefficient (NSC), so it is not displayed.

C1	C2	C3	C4	C5	C6	C7	C8
SURLAG	...	SOL_ORGP	RUNOFF	WTRYLD	SEDYLD	ORGPYLD	SOLPYLD
4		125	340.76	716.11	3.521	1.219	0.55
4.2		125	340.76	716.16	3.561	1.228	0.55
4	...	125	403.77	721.09	4.179	1.392	0.646
4		125	344.96	741.97	3.567	1.233	0.563
4		125	340.76	716.18	3.521	1.219	0.55
4	...	125	340.54	716.64	3.789	1.275	0.547
4		125	340.76	716.11	3.521	1.219	0.55
4		125	340.76	716.11	3.521	1.219	0.527
4	...	125	340.76	716.11	3.521	1.219	0.555
4		125	340.76	716.11	3.521	1.219	0.565
4		131.25	340.76	716.11	3.521	1.26	0.551

Example 6. A typical senabs.txt file (The numbers in the first row are column labels; they are not contained in the real file)

C1	C2	C3	C4	C5	C6	C7	C8
SURLAG	...	SOL_ORGP	RUNOFF	WTRYLD	SEDYLD	ORGPYLD	SOLPYLD
4		125	0	0	0	0	0
4.2		125	0	0.2499	0.2000	0.045	0
4	...	125	17.26	1.364	0.1803	0.0474	0.0263
4		125	88.42	544.4	0.9684	0.2947	0.2737
4		125	0	66.67	0	0	0
4	...	125	-42.31	101.9	51.53	10.77	-0.5769
4		125	0	0	0	0	0
4		125	0	0	0	0	-0.0051
4	...	125	0	0	0	0	0.4167
4		125	0	0	0	0	0.020
4		131.25	0	0	0	0.0066	0.0002

Example 7. A typical sensen.txt file

The third SENSAN output file ("sensen.txt") provides model output sensitivities with respect to parameter variations from their nominal values. Parameter nominal values are assumed to reside on the first data line of the parameter variation file. Sensitivity for a particular model output is calculated as the difference between that model output and the pertinent model output "nominal" value (highlighted values in Example 6), divided by the difference between the current parameter set and the parameter nominal values. If only a single parameter P differs from the nominal set, the sensitivity for a particular model output Φ is defined as:

$$\frac{\Phi - \Phi_0}{P - P_0} \tag{1}$$

Where Φ_0 and P_0 are model output and parameter nominal values and Φ and P are the model output and parameter values pertaining to a particular model run. An example of the `sensen.txt` file is presented in Example 7.

2. Calculating Normalized Sensitivity Coefficient (NSC) Using MS Excel

The normalized sensitivity coefficient (or sensitivity index) is calculated through the following formula:

$$NSC = \frac{(\Phi - \Phi_0)/\Phi_0}{(P - P_0)/P_0} = \frac{\Phi - \Phi_0}{P - P_0} \times \frac{P_0}{\Phi_0} \tag{2}$$

Or

$$NSC = \frac{|\Phi - \Phi_0|}{|P - P_0|} \times \frac{|P_0|}{|\Phi_0|} \tag{3}$$

Where, the NSC is a dimensionless positive number, whose value indicates the relative importance of parameter P on the model output Φ, that is, the relative sensitivity of the particular model output Φ with respect to the changing of the particular model parameter P.

The following steps illustrate how to calculate the NSC's from the two SENSAN output files (`senabs.txt` and `sensen.txt`) using MS Excel.

Step 1: Create a new spreadsheet file named the current worksheet as `surface runoff`.
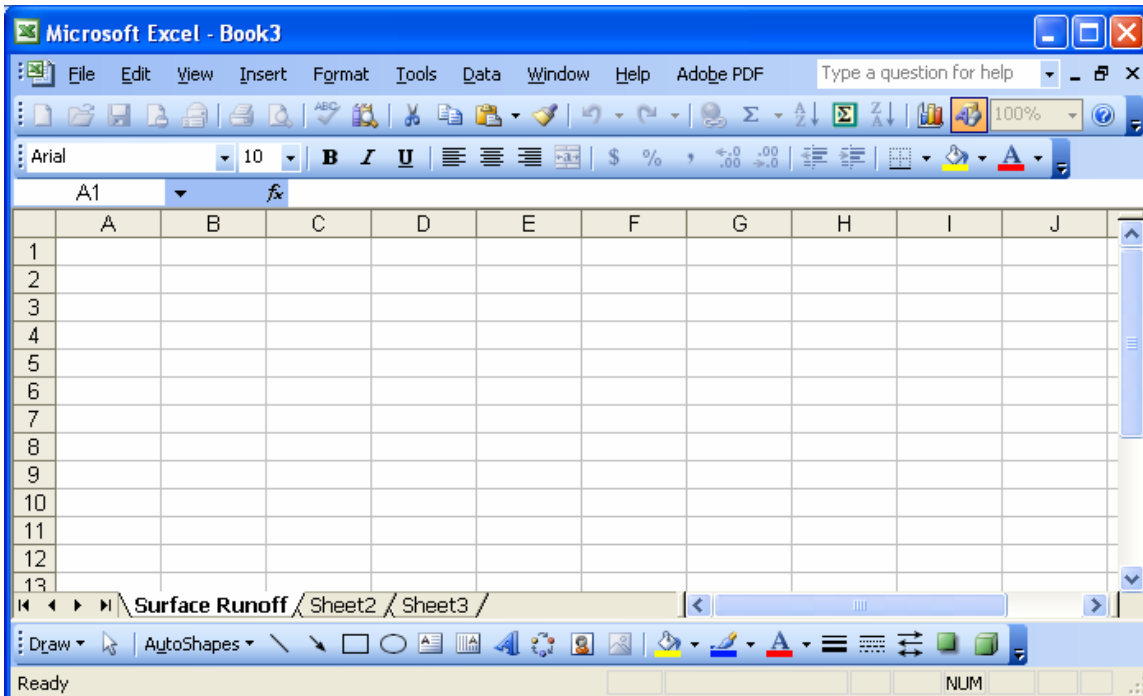
Step 2: Using MS Excel File Import Wizard to open the senabs.txt file and copy the 10 parameter names and their nominal values.
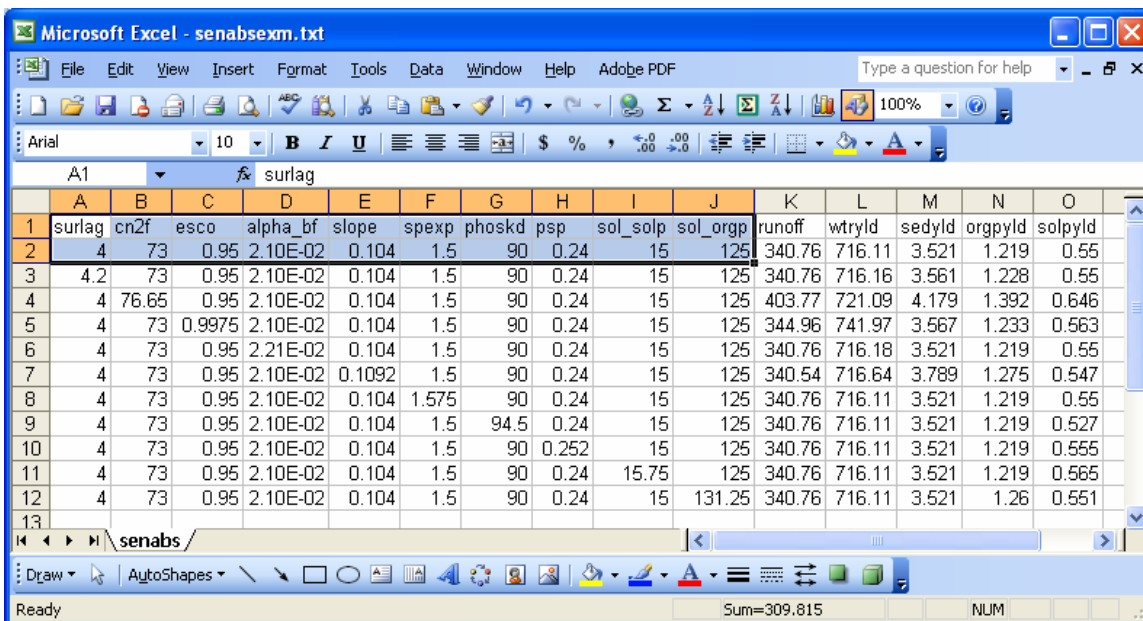
Step 3: Place cursor in Cell A2 of surface runoff; right click and select Paste Special … on the pop-up menu; and check the box in front of Transpose.

Step 4: The copied parameter names and their nominal values are pasted in `surface runoff` in a transposed manner.
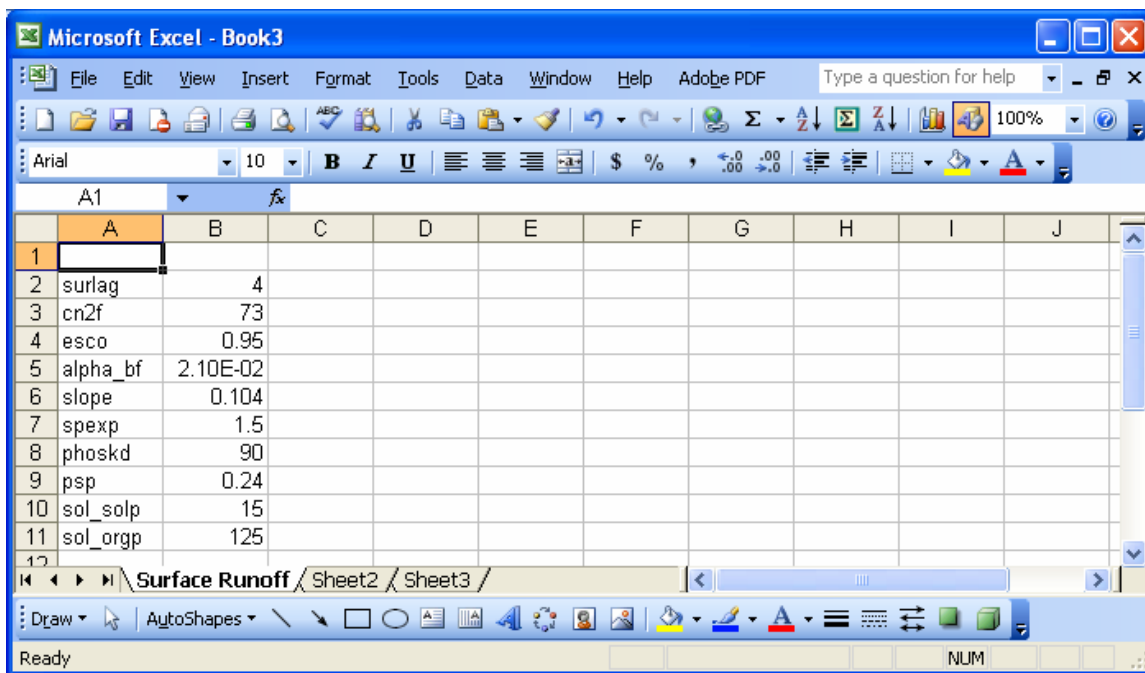
Step 5: To calculate the sensitivity of surface runoff with respect to the 10 SWAT parameters, we give names for the columns as shown below.
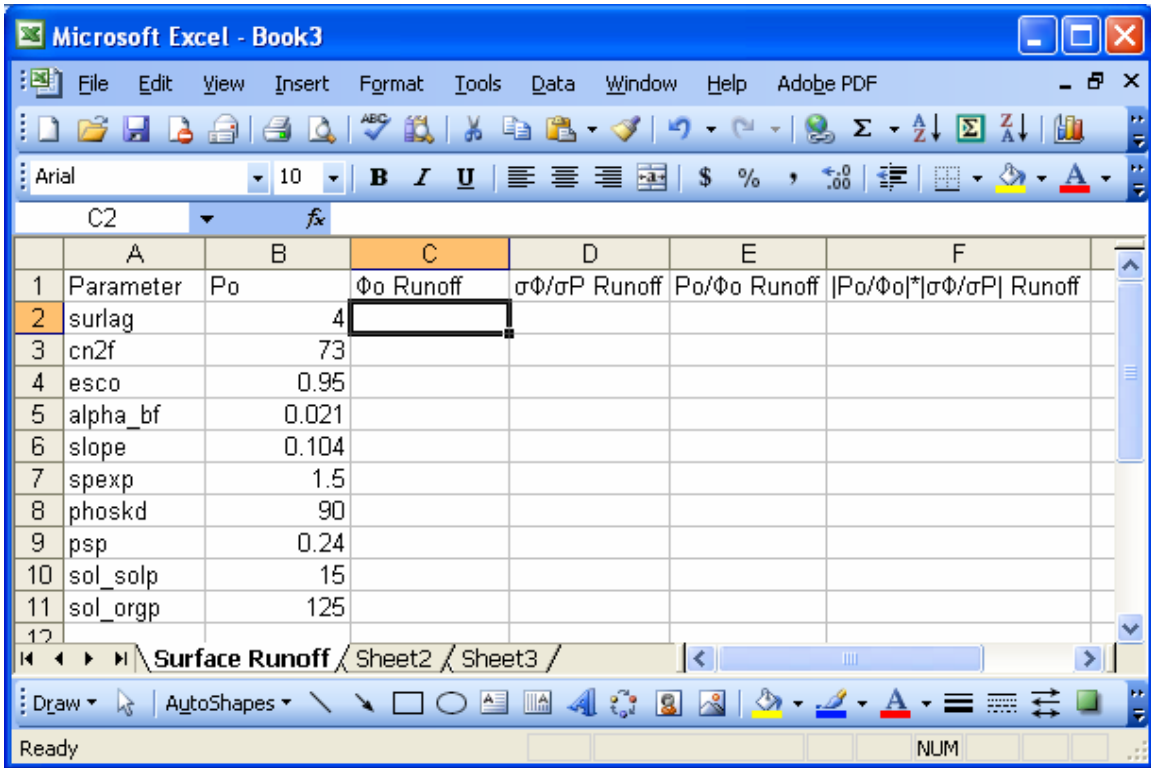
Step 6: From `senabs.txt` file we copy the "nominal" value of surface runoff (340.76 mm).
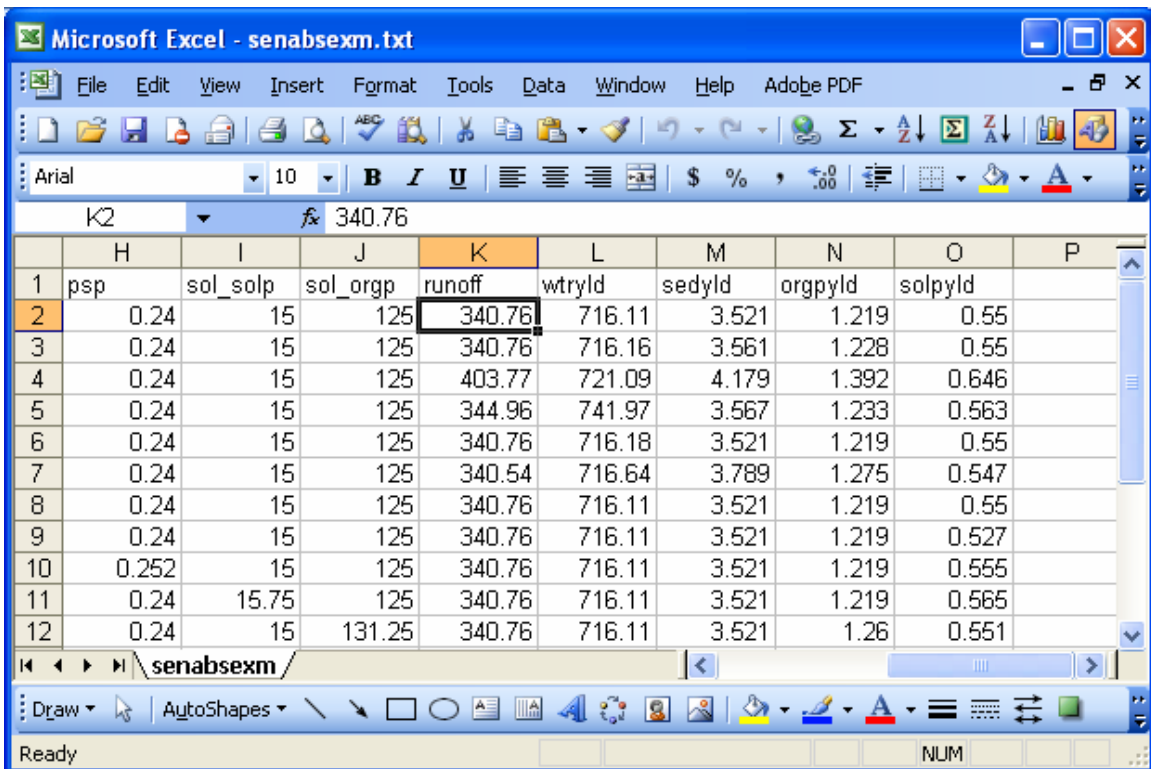
Step 7: Paste to the third column of `surface runoff.xls`.

Step 8: Open `sensen.txt` file and copy the column of "runoff" starting from Row 3 (omitting the first data line).

Step 9: Paste to `surface runoff.xls`.

Step 10: Calculate P_0 / Φ_0 for surface runoff.

Step 11: Calculate NSC (Equation 3).

Step 12: Fill the rest row of the last two columns. Therefore, the last column contains the normalized sensitivity coefficients of the 10 parameters with respect to surface runoff.

Step 13: Following Steps 1-12 to calculate the NSC's of the parameters with respect to other model output variables such as total water yield, sediment yield, organic-P yield and soluble-P yield.