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# Continuous hydrologic modeling with HMS in the Aggtelek Karst region

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**Abstract:** Karst aquifers have complex groundwater flow patterns. In Hungary, Aggtelek is one of the best-studied karst regions. Research started in the early 1960's to study the surface and subsurface hydrology of the region. Data collected included hydro-meteorological measurements, surface flow experiments and analyses, direct and indirect determination of karst infiltration, and water level measurements in karst wells. Between 1959 and 2000, daily measurements were conducted at the 15 largest karst springs. Creating a robust prediction model for this area has been elusive. This paper discusses the development, parameterization and calibration of the soil moisture accounting (SMA) method in the Hydrologic Modeling System (HMS) for one of the watersheds in this region. Parameters were studied with respect to sensitivity in generating baseline outflows for the watershed. The model was calibrated using a eight-year span of data and five different statistical measures to determine goodness-of-fit. Once calibrated, the model was used to predict baseline flow for other time periods and the results compared to measured data. The model produced reasonable results, but illustrated the need for more refined application of specific parameters.

**Keywords:** Hydrologic Models, Karst Region, Calibration

## 1. Introduction

Increased water demands from population shifts, droughts, agricultural and industrial development have focused attention on groundwater resources in Hungary and concerns for the sustainability of springs throughout the country. One of the most treasured spring resources in Hungary is the Aggtelek region; part of a UNESCO World Heritage Site shared with Slovakia. The region has been a focus for study over a long period of time and data has been collected for over 30 years by researchers [1].

There are many methods to investigate and characterize karst hydrology, including water budget, conduit system response, spring discharge hydrograph analyses, precipitation response analyses, and numerical modeling [2]. The water-balance method [3][4] can be used to estimate karst aquifer recharge. The method is based on direct monitoring, and used for the duration of observations. Since there has been long term data in the Aggtelek region, this method has been applied to estimate future recharge in springs[1]. Additionally, basin flow characteristics can be determined by interpreting the spring flow recession curve [5]. Lumped approaches [6] [7] [8] can model the entire karst system. However, numerical modeling has become an important, commonly-applied tool for complex hydrological relations. The importance of the conduit geometry was assessed with the EPA SWMM model while distributed and semi-distributed models were used to describe the karst system [9]. Modflow has also been used for large-scale watersheds [10] to analyze karst aquifers. The HEC-HMS model was applied to the Coulazau River to model surface flow on karst watersheds [11].Other studies [12][13] conducted sensitivity analyses and calibrated the continuous model in HMS for large, but not karst, watersheds. The objective of this study was to evaluate the accuracy of the HMS model with the Soil Moisture Accounting (SMA) component to model karst aquifers. Use of the continuous SMA component for modeling karst systems has not been attempted before to the best of the authors' knowledge. A continuous model can be attempted because of the fortuitous circumstance of long-term data collection in this region. This paper focuses on applying the HMS SMA model into the framework of the Aggtelek conceptual model.The main focus is on calibration and validation procedures, and evaluating parameter sensitivity of the model.

# 2. Description of the Study Area

## *2.1. Study Site*

The Aggtelek-mountain region is located in the NE part of Hungary, directly neighboring Slovakia, with an area of about 202 km$^2$(Fig. 1). This is the southern carbonate ridge of the northern Carpathian Mountains. Karst plateaus rise along an east-west direction to an elevation 400-600m high. The main mass of the mountain is Triassic sediment. The lower Triassic sediment is a clay and sandstone aquitard, overlain by clayey middle- and upper-Triassic sediment with carbonaceous dolomite, and limestone.The area of the lower Triassic aquitard is 62 km$^2$, while the limestone-dolomite surface area is 105 km$^2$. In the South-South West part of the region there is a 35 km$^2$ area, that is mostly impervious sediment that contains Pliocene, Pannon-aged clay, sand, and gravel. The karst plateaus are overlain by Pleistocene agedclayey soil, mostly 20-50 cm thick, sometimes 1 m thick.The Aggtelek watershed is about 70 km$^2$. Work started in the early 1950's by the Ferenc Papp Research Station to study the surface and subsurface hydrology of region. They included hydro-meteorological measurements, surface flow experiments and analyses, direct and indirect determination of karst infiltration, and water level measurements in karst wells. Fifteen major springs were monitored from 1954-2000, [14].

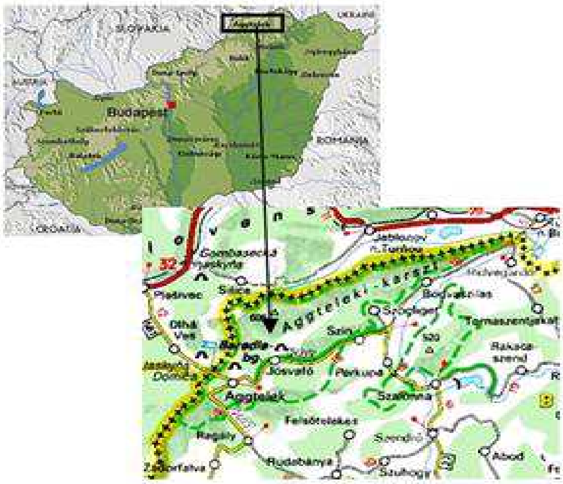


***Figure 1.****The Aggtelek region*

Additionally, several recording and non-recording rain gages were also used during this time. The monitored springs can be divided into 3 distinct hydrological regions shown as ovals in Fig.2.

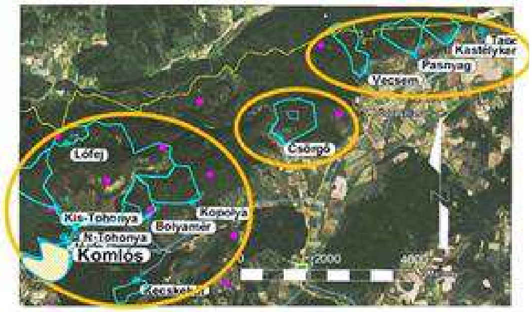


***Figure 2.****. Aggtelek watersheds.*

Springs around the Jósvafő area are on the left side. In the center is a single spring Csörgő,andfour springs in the NE area. The delineated watershed areas for these springs are shown as polygons in Fig 2.

This study focuses on the Komlós spring (shaded watershed), located near the south western border ofthen Jósvafő area. Komlóshas a continuous(1958-1993) daily-measurement of rainfall, temperature, and spring flow data. It's area is approximately 2.0 km$^2$,andit receives an average annual precipitation of 650 mm. Surface elevation in the watershed ranges from 217m (at the spring) to 440 m.

## *2.2. General Conceptual Model*

Water recharged into karst aquifers moves down-gradient through a combination of highly anisotropic pathways. Using a triple porosity approach, the Aggtelek model (Fig 3.) was developed[4]. The karst aquifer is divided into the following components: (1) The major conduit network with sinkholes, (2) The tributaries of the conduit system with sinkholes, (3) The major fracture system above base level, (4) The matrix of small lateral fractures throughout the karst blocks, (5) The system of micro-fractures within the same matrix, (6) Deepkarst fractures below the conduit system (Fig. 3).

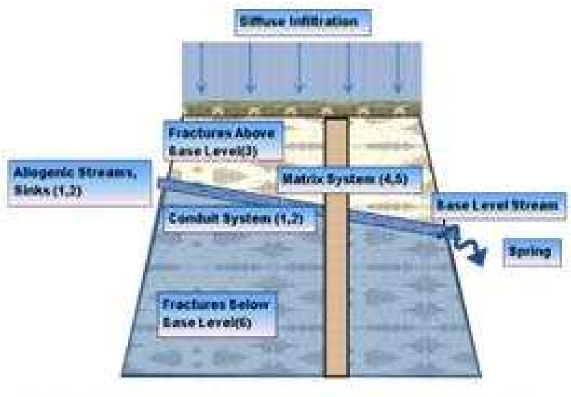


***Figure 3.****. Aggtelek aquifer conceptual model.*

The computational model was developed based on this framework (Fig 4). Precipitation falling onto the drainage basin can be divided into diffuse infiltration,internal runoff, and surface runoff. Diffuse infiltration occurs where rainfall from the surface infiltrates into the soil and fractured matrix (4, 5). Internal runoff occurs when surface water flows into closed depressions and enters the aquifer system through major fractures above base level(3) and eventually reaches the conduit system (1, 2).

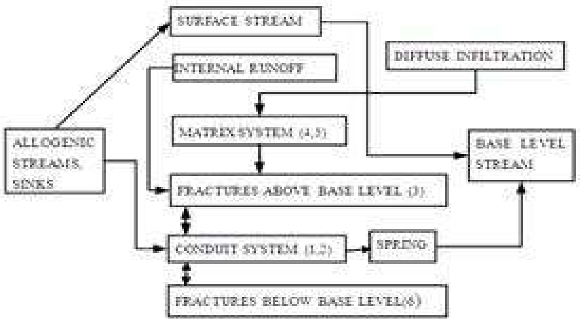


***Figure 4**.. Computational model, Aggtelek aquifer (mod.[15]).*

In this case the overland flow from either allogenic or surface streams plays a very small role in the Aggtelek region, accounting for lessthan 1% of the base level stream flow.

## 3. Methodology

### *3.1. Continuous Model Structure*

The watershed runoff process in the continuousHMS-SMA model starts with precipitation. It can fall on the watershed canopy vegetation or land surface. Some of the water returns to the atmosphere in the form of evaporation from the canopyand land surfaces except during a storm event when evaporation is limited. Some precipitation falls through the canopy, where it joins the water which fell on the land surface. Depending on the soil type, ground cover, and antecedent moisture conditions,the water may pond and a portion may infiltrate. This infiltrated water is stored temporarily in the upper, partially-saturated layers of soil. It can rise by capillary action toward the surface, movehorizontally near the ground surface as interflow, or percolate vertically downward into the aquifer. Horizontal interflow will eventually reach the stream channel. Water percolating downward through the aquifer moves more slowly, but will also eventually reach the channel stream as baseflow. The linear–reservoir model is typically used with the SMA model in baseflow calculations.

This model simulates both dry and wet weather behavior. It tracks water movement and storage in the vegetatedzone as well as freestanding water on the soil surface. Additionally it will model water movement and storage in the upper soil profile, and lower groundwater layers.

### *3.2. AggtelekModel*

The meteorological component of HEC-HMS was used to model rainfall, snowmelt, and evapo-transpiration(E-T). The SMA model was applied to the upper matrix system component of the karst hydrology model as shown previously in Figs 3 and 4. A schematic representation of the SMA model appears in Fig. 5. Given precipitation and maximum potential E-T, the model computed losses due to E-T, basin surface runoff, storage and percolation between soil zones, interflow and groundwater flow and finally,deep percolation out the bottom of the entire basin. The SMA represents the watershed with a series of storage layers: canopy interception, surface depression, soil profile, and groundwater storage. Current storage contents are calculated during simulation and vary continuously both during and between storms. During simulation, E-T is not triggered if precipitation occurs; if no precipitation occurs then E-T does occur.

Translating the karst computational models in Figures 3 and 4 to HMS-SMA was done in the following way. Diffuse infiltration included water moving through the soil surface and into the topsoil above the karst system. Groundwater storage 1 represents the top soil, whilegroundwater storage 2 represents the matrix system (4, 5). Water percolates into the topsoil and matrix system vertically, then later laterally to the spring as interflow and base flow, respectively. Fractures above base level(3) and the conduit system (1, 2) were not modeled in the SMA system.

For the surface flow component, the Clark unit hydrograph was selected.

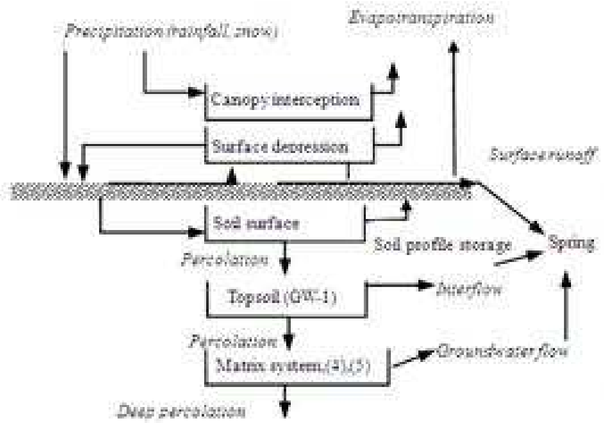


***Figure 5.** Soil moisture accounting model for Komlós.*

### *3.3. Model Parameter Estimation*

Rainfall data from one gagein the watershed was assumed to be uniformly distributed over the watershed. The monthly evapo-transpiration was estimated based on the Thornthwaite-method[16] using the recorded temperature data. Snow accumulation and melt was modeled with the temperature index method.

The SMA and base flow input parameters were determined based on previous field work and modeling[3]. Canopy storage was assumed to be 10 mm and surface storage 20mm. The topsoil was assumed to be sandy loam, 100 cm deep, with 0.3 porosity, 0.2 air entry value, and 0.1 wilting point. Soil storage was 0.2mm/mm, and tension storage 0.1 mm/mm of soil depth. The matrix system porosity was determined in an earlier study, as 0.38 and it was assumed to be 10m deep. Release times were determined to be 480-4080 days; the linear recession coefficient for the matrix system was assumed to be 650 hr.

### *3.4. Model Calibration and Validation*

An 8-year time period,from1975 to 1982, was selected for calibration. It contains a wide range of large and small rainfall events. During model calibration, parameters were adjusted until acceptable comparison was found between the modeled and measured spring flow data. Both automated and manual calibration procedureswere attempted. The peak-weighted root-mean-square error objective function with the univariate gradient method was used to calibrate the HMS model. However, calculated parameters generated by the program were not always reasonable. Therefore,a more systematic approach to the manual method was usedto determine optimal parameters for the model. Initially, a reasonable set of parameters were determined, then a calibration scheme was defined. One of the given parameters was changed in value while the others were held constant. The output of the manual calibration was assessed by flow comparison graphs, and the goodness-of-fit measures, using functions described by [13]. Five goodness-of-fit measures were selected: peak-weighted root mean square error (PWRMSE), lag-0 cross correlation coefficient (CORR), relative bias (RBIAS), relative root mean square error (RRMSE), andpercent error in volume (PEV) shown in Table 1. The parameters were adjusted until the four goodness-of-fit measures were minimized (PWRMSE, RBIAS, RRMSE, PEV, and the correlation coefficient (CORR) was closest to one.

***Table 1.****List of statistics used to compare model output and observed data*

| Statistics | Equation |
|---|---|
| PWRMSE | $\left\{\frac{1}{N}\left[\sum_{i=1}^{N}(Q_o(i)-Q_m(i))^2\left(\frac{Q_o(i)-\overline{Q}_o}{2\overline{Q}_o}\right)\right]\right\}^{0.5}$ |
| CORR | $\frac{\sum_{i=1}^{N}(Q_o(i)-\overline{Q}_o)*(Q_m(i)-\overline{Q}_m)}{\sqrt{\left[\sum_{i=1}^{N}(Q_o(i)-\overline{Q}_o)^2*\sum_{i=1}^{N}(Q_m(i)-\overline{Q}_m)^2\right]}}$ |
| RBIAS (%) | $100*\frac{1}{N}\sum_{i=1}^{N}\frac{(Q_m(i)-Q_o(i))}{Q_o(i)}$ |
| RRMSE (%) | $100*\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{(Q_m(i)-Q_o(i))}{Q_o(i)}\right)^2}$ |
| PEV (%) | $100\left\|\frac{V_o-V_m}{V_o}\right\|$ |

Note: $Q_o$=daily observed springflow; $Q_m$=daily modeled springflow; $\overline{Q}$=average springflow; $V_o$=observed springflow volume, $V_m$=modeled springflow volume

During validation,only the initial conditions were changed in order to model the 1983-1992 observational periods. In 1990, it appeared that there were no spring flow measurements, but the simulation continued, and extended one more year.

### *3.5. Sensitivity Analyses*

The final parameters used in the calibrated model were considered a baseline parameter set. The model was then run repeatedly with the baseline value for one parameter multiplied by 0.8 and 1.2, while keeping all other parameters at their baseline values. The hydrograph of the changed parameter model was then compared to the baseline model hydrograph. The performances were evaluated based on the statistics listed in Table 1. Out of the 24 parameters used in the SMA model,10 were selected for sensitivity analyses. The initial moisture state parameter values for canopy, surface storage, and surface flow were not varied in the sensitivity analyses since these parameters would only influence the first season model results.During calibration, surface capacity and soil percolation did not have a significant impact on the model results; these parameters were also not included.

## 4. Results

Table 2 shows the SMA parameters after calibration. The calibrated matrix system parameters (MS, MC) are at least 50% lower than the original estimates. Matrix system out-percolation rate was set to zero during modeling, since there was no field evidence for assuming a non-zero value.

In Fig. 6, the modeled and observed flowsare compared. The peaks flows are under-predicted in almost all cases during the summer season. In the winter seasons, the peak flows are over-predicted, indicating a seasonal change in the loss parameters. During the summer season, the model predictssmallpeaks when very little flow occurredin the

***Table 2****. Input parameters for the SMA model*

| Parameter description | Calibrated value |
|---|---|
| Surface Capacity (mm) | 10 |
| Soil Storage, SS (mm) | 200 |
| Tension Storage, STS (mm) | 100 |
| Soil Infiltration Rate, SI (mm/hr) | 100 |
| Soil Percolation Rate(mm/hr) | 10 |
| Topsoil Storage, TS (mm) | 150 |
| Topsoil Percolation Rate, TP (mm/hr) | 10 |
| Topsoil Coefficient,TC (hr) | 15 |
| Matrix system Storage, MS (mm) | 100 |
| Matrix system Out-Percolation Rate, (mm/hr) | 0 |
| Matrix system Coefficient, MC (hr) | 15 |
| Linear Reservoir Topsoil Coefficient, RTC (hr) | 50 |
| Linear Reservoir Ms Coefficient, RMC (hr) | 650 |

spring. Evaporation values were adjusted to reduce the flows, but during large storms, evaporation is calculated only after rainfall ceased, which may or may not be true.

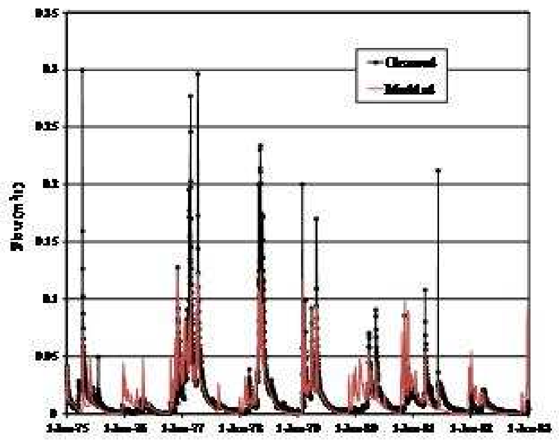

***Figure 6.**Observed and modeled hydrographs for calibration between 1975-1982.*

The result of the validation procedure is shown in Fig. 7. The modeled hydrograph show a reasonably good fit tothe measured data. During the winter season, the program predicted some flow when no significant spring flow was measured. During summer, the peaks were again under-predicted for wet periods.

Statistical results for both the calibrated and the validated casesare shown in Table 3. The percentage of volume (PEV) for the model is small, as well as the peak weighted root mean square error. Correlation and relative bias gave moderate results, while the relative root mean square error is very high.

The result of the sensitivity analyses is shown in Fig 8. For PEV, the value of tension zone depth generated the highest errors. The impact of the other parameters was much less significant. Two parameters; tension storage, STS, and

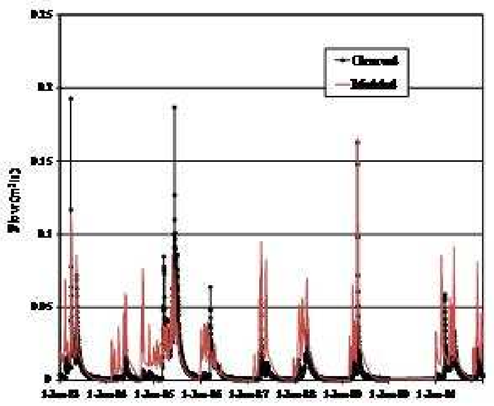

***Figure 7.**Observed and modeled hydrographs for validation between 1983-1992.*

topsoilco efficient, RTC, generated hydrographsthat agreedless with the baseline data,based on the correlation coefficient, CORR. The relative BIAS for values for STS, and RMC were greater than 20%. The rest of the parameters were all less than 10%. By reducing the STS value by 20%, the relative bias increased by 120%. The relative RMSE for the different scenarios of the ±20% change was evaluated as well. The highest value was obtained with the STS, and RMC parameters (100%, and 70%, respectively). Highest sensitivity was observed with the STS, and RTC parameters, but the other parameters showed moderate sensitivity as well.

***Table 3.**Statistical performance measures for calibration and verification*

| Statistics | Calibrated value | Validation value |
|---|---|---|
| PWRMSE% | 3.85 | 2.17 |
| CORR | 0.72 | 0.60 |
| RBIAS (%) | 55.52 | 225.02 |
| RRMSE (%) | 292.08 | 557.31 |
| PEV (%) | 4.66 | 23.18 |

# 5. Conclusion

A numerical model was developed to describe the complex flow characteristics of a karst aquifer. In this paper it was demonstrated that applying a multipart meteorological model combined with the soil moisture accounting model can predict spring flowsfrom a karst aquifer with reasonable accuracy. Such an application has not been attempted before.

Predicted flow showed a seasonal preference; in the summer season peak flows were under predicted, in the winter over-predicted. Seasonal parameterization mayhelp model accuracy, as it was shown in other studies [12] [13]. Also, for small summer storms, flows were over-predicted, indicating that for daily time steps it is not reasonable to assume that no E-T occurs.

Sensitivity analyses showed that the soil tension depth plays a significant role, in model accuracy. The second most import set of parameters in the SMA model were the base flow linear reservoir parameters. These results are similar to those concluded in an earlier study [13].Since the surface infiltration rate is much higher than the soil percolation, there is a greater influence from soil surface parameters. Estimation and calibration procedures need a more accurate determination of this parameter.

Goals of further study include model parameterization using geographic information system, and further refinement of the fracture networks to improve parameter estimation.

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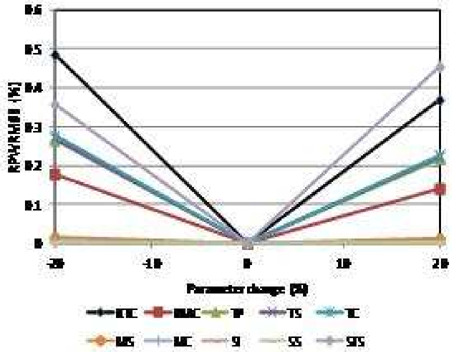


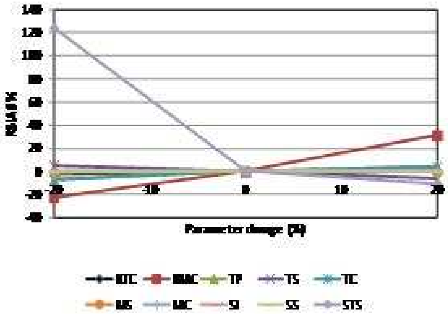


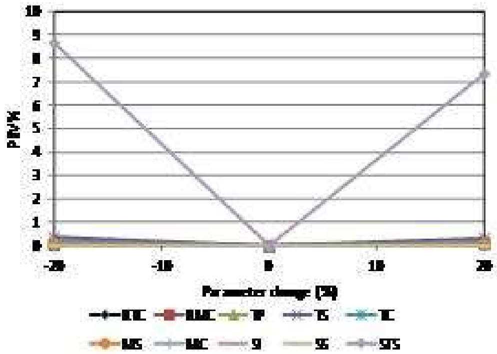


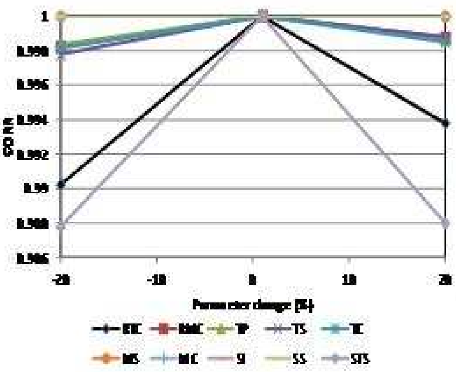


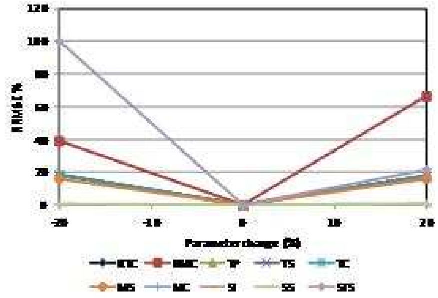


***Figure 8.****Statistical measure for sensitivity scenarios*

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