The Utility of a Pollutant Load Screening Model in Determining Provisional Pollutant Load Reduction Goals

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Abstract: Screening-level watershed models have been widely used in water resource management planning. Should such models be used only as initial tools for very generalized planning, or do some of these coefficient-based models have a greater utility? The Pollutant Load Screening Model (PLSM) (Adamus & Bergman, 1995) was used to determine past, present, and future annual loads of total nitrogen, total phosphorous and total suspended solids stemming from various watershed basins within the Indian River Lagoon (IRL). This work has largely been performed to establish interim pollutant load reduction goals (PLRGs) based on estimated 1943 loadings for priority watersheds within the IRL. Yet, were these reasonably reliable numbers?

In an effort to begin to answer this question, results from the application of PLSM were compared to those obtained from three established watershed models for the drainage basins in which they were developed. The results of that comparison show that when well-developed land-use and soils data are available, PLSM generates annual loads of nitrogen, phosphorous and suspended solids that are comparable to the other, more complex watershed models that were calibrated within their respective watersheds.

Introduction

A number of screening-level watershed models have been developed for use in water resource management planning, but how much reliance can be placed on the actual numbers generated by such models? Should screening models be used only as initial tools for very generalized planning, or do some have greater utility? The Pollutant Load Screening Model (PLSM) is a Geographic Information System (GIS) model developed by Christine Adamus and Martinus Bergman (1993, 1995) that uses simple mass balance algorithms to estimate annual loads generated by land uses combined with their underlying soil types.

The model was originally developed as a planning tool for identifying stormwater runoff problems and providing long-range guidance in growth management. Given its original intended use, there were no initial attempts to calibrate the model or test it against measured data. However, with growing interest in the possibility of using PLSM to set provisional pollutant load reduction goals (PLRGs) within the Indian River Lagoon (IRL), there arose a need to test the model's reliability at predicting non-point source loads of total nitrogen, total phosphorous and total suspended solids. If the model proved to be reasonably accurate, it could then be used to estimate the load reductions needed to return to 1943 levels—the provisional PLRGs.

Reasons for turning to PLSM center on the ease and speed with which it can be set up and run in nearly any drainage basin. Unlike more intricate, process-based models, it requires only a modest amount of basin-specific data. The model's input requirements are summarized below.

Spatial Data Layers: drainage boundary, land use, soil type, and annual rainfall.

Runoff Coefficients: volumetric ratio of rainfall excess (runoff) to total rainfall derived from literature, conversion of curve numbers (CN), or calculated from the ratio of pervious to impervious surface area for a particular land use group (Harper, 1994).

Runoff Concentrations: literature values derived from field studies.

BMP Treatment Efficiencies: literature values applied to development occurring after stormwater rule implementation.

With the widespread use of GIS and the minimal input data requirements, PLSM is very portable. Of course, this simplified relationship of land use to loading is the main limitation in its ability to accurately predict runoff loads. This was a source of initial concern. Could such a simplistic "inference-based" model provide accurate enough results to establish provisional PLRGs?

The first and foremost problem with testing PLSM lies in the fact that it is a *runoff* model. The vast majority of the loading data available for comparison pertained to total watershed loadings, which include the contribution from stream baseflow. Field data on direct runoff loads was either not available or unusable; therefore, PLSM load estimates were preliminarily compared to total annual loads measured in two different basins. The results for TN and TP were surprisingly close, but one had to question whether this apparent accuracy was real or coincidental?

Methods

In our attempt to answer the question of "is it real", PLSM was run in four different drainage sub-basins with the IRL: Crane Creek, C-1 Canal of Turkey Creek, South Prong of Sebastian River, and Briar Creek. The location of each is shown in Figure 1. The selected sub-basins provide a good cross section of the land use composition within the Lagoon. Dominant land use types among the four sub-basins vary from urban development to agriculture to forest and rangeland. Total annual loads of nitrogen, phosphorous and suspended solids were computed then compared to both measured data and loads estimated by other watershed models that were developed and calibrated, each within one of the sub-basins.

Like all models, PLSM can only be as accurate as the data used for input. The first group of these is the GIS data layers. Land use data typically has the inherent problem in that its classification system is designed to serve many masters. That is to say such data is not usually developed with the explicit intent of being used to predict runoff loads. For this purpose, additional quality assurance is almost always required. Direct knowledge about the "lay of the land" and its management is invaluable. One example of the level of QA undertaken in this study is the distinction between improved and unimproved pasture. In one of the sub-basins, land use maps indicated it contained about 3,100 acres of improved pasture. After reviewing some previously published reports on loading from this sub-basin and receiving anecdotal reports from land appraisers and managers, about 2,600 acres (84%) were reclassified to unimproved pasture, a category with a much lower areal loading rate. In another basin, an unusually large area was classified as airport. Though the airport property was indeed quite extensive, upon closer inspection it was observed that much of this was being leased for commercial development such as hotels and businesses. A final example was the designation of military bases as "institutional". Review of aerial photographs showed that a large portion of one base was undeveloped and needed to be reclassified accordingly.

Other required data layers are the delineation of different soil types and annual rainfall volumes. For this study, scanned and geo-rectified U.S.D.A. Soil Conservation Service (SCS) soil survey maps within the SRJWMD database were used. However, these maps have limitations as to the spatial accuracy of the boundaries between soils as well as in the photo-interpretive methods used for classification. Rainfall volumes can be highly variable over relatively short distances on any given day or month. The use of annual rainfall volumes reduces this variability to a certain extent, but rainfall volumes can still vary significantly from year to year. The runoff coefficients used in PLSM are based on soil storage conditions during average (30-year mean) annual rainfall. Very wet or dry years will skew the results because of the changes it creates in the storage capacity of the watershed soils. In addition to these temporal problems, there is the matter of spatial accuracy. Having a well-placed grid of rainfall monitoring stations with quality assured data is important. Unfortunately, there are almost always gaps in any network across which rainfall will have to be interpolated and this study was no exception. Mean annual (30-year rainfall data came from established Nation Weather Service (NWS) stations. Annual rainfall volumes used for particular years were a synthesis of NWS stations and data collected from the District's hydrological/meteorological network.

The error associated with the above data layers is somewhat universal to all watershed models. The error associated with the use of runoff coefficients and land-use mean concentrations are more specific to PLSM. To reduce this error as much as possible the concentrations and coefficients used in this study came from a pool of literature published on studies performed within the state and—as much as possible—within the region. This body of information was supplemented with field data collected within the IRL basin.

Calibration of the land-use concentrations was conducted simultaneously over all four sub-basins to achieve a best overall fit. Land-use sensitivity (the product of runoff volume and event concentration expressed as the percent of the total load) was analyzed to determine which changes would have the greatest impact within each sub-basin. For the most part, runoff coefficients were left unchanged since estimated flow volumes compared reasonably well with measured data. However, to account for annual variance in soil storage, correction factors were applied to the calculation of total discharge. A correction factor was used if the average annual rainfall recorded during the calibration period was greater or less than the 30-year mean by ten percent. In such cases, a multiplier was included in the PLSM calculations of total discharge from the watershed. This multiplier is the quotient obtained from dividing the annual rainfall recorded during the study period by the 30-year mean.

Treatment efficiency coefficients were integrated into the model in an attempt to account for stormwater treatment provided with development occurring after the implementation of stormwater rule criteria imposed by the state of Florida. The coefficients used are highly generalized, representing an average of values reported in literature for the most common type of stormwater BMP utilized within the IRL drainage area—the wet detention pond. As such, the following load reduction factors were used: TN—30%, TP—50%, TSS—70%. The accuracy in determining which areas to apply the treatment coefficients was limited by the time period of available land use data that would serve as the baseline. Stormwater treatment rules first went into effect in 1984, but the land use layer nearest to that year was one developed from 1989 aerial photographs.

A final source of error in PLSM is the fact that it cannot easily account for in-stream processes such as settling or decay, nor can it address the loading due to stream base flow. No attempt was made account for these variables in the results presented below.

Results

As previously mentioned, calibration of land-use based event mean concentrations was carried out simultaneously over all four sub-basins. Land use sensitivity (percent contribution) provided guidance on which parameter changes would have the greatest effect. Table 1 summarizes those land use categories with the greatest influence and the sub-basins in which they were most sensitive.

Table 1. Sensitivity to land use

Land Use Type	Sub-basin Name	TN Percent of Total Load	TP Percent of Total Load	TSS Percent of Total Load
Commercial High	Crane Creek	23%	25%	35%
Citrus	South Prong	30%	48%	52%
Industrial	Crane Creek	*N/A*	*N/A*	13%
Pasture Improved	South Prong	18%	23%	17%
	Briar Creek	12%	16%	19%
Pasture Unimproved	C-1 Canal	24%	*N/A*	18%
Rangeland	C-1 Canal	13%	*N/A*	*N/A*
Residential High	Crane Creek	13%	17%	12%
Residential Medium	Crane Creek	22%	21%	12%
	C-1 Canal	33%	43%	32%
	South Prong	10%	*N/A*	10%
Residential Low	Briar Creek	20%	26%	11%
Upland Forest	Briar Creek	29%	24%	17%

After calibration, PLSM was compared to total annual loads of nitrogen, phosphorous, and suspended solids measured in each of the four drainage sub-basins over different periods of record. Individually, results varied between loading parameters and sub-basins. PLSM did a particularly good job at estimating total nitrogen in all four sub-basins, the model loads varying from measured data by as little as two percent and by no more than ten percent. Estimations of total phosphorous appeared somewhat less accurate with differences ranging from 10% to 89%. The poorest performance by the model was in predicting the annual load of suspended solids. Differences from measured data varied between 7% and 152%. Some of this apparent disparity between modeled and measured TP and TSS loading is likely due to inadequacies found in the reported sampling methods used to the collect water quality data and the resulting calculation of measured loads. This will be better explained in the discussion section of this paper.

When the cumulative annual loads measured in all sub-basins are compared to the cumulative loads estimated by PLSM (Figure 2.), one finds a similar relationship between parameters in the accuracy of the model; total nitrogen was overestimated by two percent, total phosphorous by six percent, and total suspended solids by fifty-nine percent. Such close agreement to measured annual loads of nitrogen and phosphorous are partially due to the canceling effect of over and underestimations by the model among the sub-basins.

A more realistic view of the model's predictive capabilities is seen in a comparison of the cumulative absolute value of differences between PLSM and measured data (Figure 3.). Differences in combined annual loads of total nitrogen and suspended solids changed very little, each increasing by only two percent. However, the difference in the combined annual load of total phosphorous rose from 6% to 29%. These numbers suggest a trend of PLSM to consistently provide close estimations of TN, to generally over-predict annual loads in TSS, but to yield mixed results—overestimating in some sub-basins while underestimating in others—on the annual loads of total phosphorous.

The utility of PLSM in predicting the total annual load of nutrients and suspended solids was then tested against that of other models. Three different watershed models had been previously developed, calibrated and used for predicting annual loads within three of the selected watersheds: C-1 Canal, South Prong, and Briar Creek. Two of the models, CALSIM (Pandit and Gopalakrishnan, 1997) and HSPF (Donigian, et al, 1984) are process-based, operating on continuous time-step simulation. The third, LOADSIM (Pandit and Swain, 1992), is a model similar to PLSM in that relies upon static variables and "spreadsheet" calculations. Each of three models was calibrated to water quality and flow data collected from a specific sub-basin within the study area. The models were then run to predict total annual loads from the respective sub-basins for time periods other than the calibration intervals. PLSM was run for the same intervals and/or conditions as those simulated by the other models.

Load estimates generated from PLSM were very similar to those predicted by the other models. Figure 4 illustrates the results. Overall estimations of TN, TP, and TSS differed from the combined simulated runs of the other models by –4%, 16% and –9% respectively. These numbers provide a general feel for the model's utility in accurately predicting watershed loads under varying conditions. Another means of scoring its reliability is provided in the Application Guide for Hydrological Simulation Program-Fortran (HSPF) (Donigian et al, 1984). Table 2 summarizes the results according to the criteria contained in the referenced publication.

Table 2. Rated cumulative results of PLSM to Measured loads

Pollutant	PLSM total	Rating	PLSM absolute	Rating
TN	2%	Very Good	4%	Very Good
TP	6%	Very Good	29%	Good
TSS	59%	Poor	61%	Poor

Discussion

The evidence that PLSM consistently generates very good estimations of total nitrogen may be due to the composition of TN by its constituent forms. Data collected from IRL tributaries during baseflow and storm events indicate that organic nitrogen comprises roughly 80% – 90% of the total nitrogen load. Further, 75% – 80% of the total organic nitrogen is dissolved in the water column. This particular form of nitrogen (DON) is somewhat resistant to the kind of in-stream processes that are problematic to PLSM. Conversely, dissolved inorganic phosphorous (DIP) typically comprises close to half of the TP load. This form of phosphorous is quite available for biological uptake by aquatic macrophytes and algae. There is also a significant component of TP that is particulate (sediment attached) in nature and, therefore, susceptible to settling. These in-stream processes may account for much of the differences seen between total phosphorous estimates of PLSM and the loads from measured data. Even so, PLSM did a good job at simulating the annual load of total phosphorous in all but one sub-basin.

Another possible source of disparity between modeled and measured TP loads is the manner in which some of the data was collected and used. In a basin-by-basin comparison of PLSM to measured data, annual TP loads differed by –16%, 34%, -27% and 89%. The latter value resulted from comparisons in the C-1 Canal sub-basin. Within any sampling program some level of error is introduced by the method of data collection. The range of concentrations for total phosphorous fluctuates more widely over time than for total nitrogen due to the composition of its constituents. This makes accurate sampling for the pollutant more difficult during storm events.

In the C-1 sub-basin, collection of measured data occurred over the course of the year in which only 80% of normal rainfall fell. Four storm events were captured for the year in which there were only nine storms recorded (Trefry and Feng, 1991). The discharge record presented with the sampling data suggests that a significant portion of the rising limb of the hydrograph (including the first flush) was missed by the sampling effort in at least one of those events. Dierberg (1991) reported a significant increase in the “first flush” concentration of TP in earlier captured storm events. Since the flow-weighted average values from the four events were then used to estimate storm loadings for the entire year, it is likely these reported loads under represent the actual mass of phosphorous discharged that year. It is also possible that the low antecedent moisture conditions persisting throughout most of that year resulted in an unusually high storage capacity in the canal system draining the sub-basin. This would create longer than expected retention times during which phosphorous could be settled or biologically assimilated. To further this argument, Trefry and Feng (1991) reported that DIP made up slightly more than half of the TP measured. As such, longer retention times in the canals would likely result in increased uptake of the dissolved inorganic component of TP with additional settling of the particulate fraction. As a final point, the areal loading rate (lb/acre) for total phosphorous measured in the C-1 Canal watershed is six to ten times below that measured in the other three sub-basins, even though it is the second most developed sub-basin in the study. This is not the case for either TN or TSS.

The worst performance of PLSM was in the prediction of total suspended solids, but not all of the data suggests it poorly simulates loading of this pollutant. In two of the four sub-basins the results were within 30% of the measured load. In comparing the cumulative difference of simulated TSS loads between PLSM and the other models, PLSM actually "underestimated" TSS loads by 9%. In the two basins where PLSM widely overestimated TSS loads compared to that calculated from measurements, the measured data itself could be called into question. Within the Crane Creek basin, water quality data used to estimate annual loads did not directly include storm event sampling. Instead, a long-term record from monthly sample collection was used. Such water quality data would almost certainly fail to record the higher TSS concentrations expected from large storm events.

The data collected from the South Prong of the Sebastian River is another example of known sampling method error. Flow from a significant portion of the South Prong sub-basin is controlled by unregulated gate structures. Storm events captured during the wet season included periods when the gates were opened. By mere chance, however, storm events captured during the dry season did not coincide with gate openings. When closed, the gates tend to act as large baffles, trapping out suspended solids until such time that they are opened, releasing the accumulated materials in large pulses. Since the dry-season event sampling missed these openings, a substantial portion of the TSS load was not accounted for in the calculation of annual loads.

A second contributing factor to the overestimation of suspended solids by PLSM is that some streams and waterways provide sufficient depth and retention time to affect a significant loss of sediment though settling. This in-stream attenuation could be roughly handled by PLSM through the addition of a scalable settling coefficient. It could also be true that some further adjustment to the TSS event concentrations used by PLSM is warranted; but before doing so, further comparison of model predictions to reliably accurate measurements will be made to provide a better sense of the model's performance.

Conclusions

When compared to available measured data, PLSM did a very good job at predicting the total annual load of nitrogen entering the IRL. The model also did a fairly good job at predicting the annual load of total phosphorous. More work is needed to determine the validity and the cause for the apparent poor performance of the model in predicting annual TSS loads.

On-going storm event monitoring within the Crane Creek sub-basin will provide greater insight to the possible need of further adjustments to land use concentrations. An in-stream settling coefficient may also aid the model in consistently producing good results on total suspended solids loadings.

The screening model performed well with respect to changes in sub-basin location, drainage area, and land use composition within the IRL. This portability along with the relative ease and low cost of set-up makes it a useful tool in analyzing annual, non-point source loadings to the IRL, especially for those sub-basins where no other calibrated models are available.

A comparison of annual loads predicted by PLSM to other watershed models calibrated within IRL sub-basins shows that the screening model produced comparable results to the more complex, process-based models. Emphasis needs to be placed on the caveat that these results are for annual loads of total nitrogen, total phosphorous and total suspended solids. Without further refinement, the model is ill equipped to simulate loading for shorter time intervals (monthly or seasonal) or years with unusual meteorological conditions such as drought. Similarly, no evidence is presented here on the model's ability to simulate non-point source loading of the various analytical forms of nitrogen or phosphorous. Nevertheless, PLSM is capable of providing reliable estimates of the total annual loads of nitrogen and phosphorous, both present and past, upon which provisional PLRGs would be based. With some additional testing and possible adjustment, we believe it will also yield estimates of annual TSS loadings that are adequate for provisional PLRG development.

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Figure 1. IRL Sub-basins

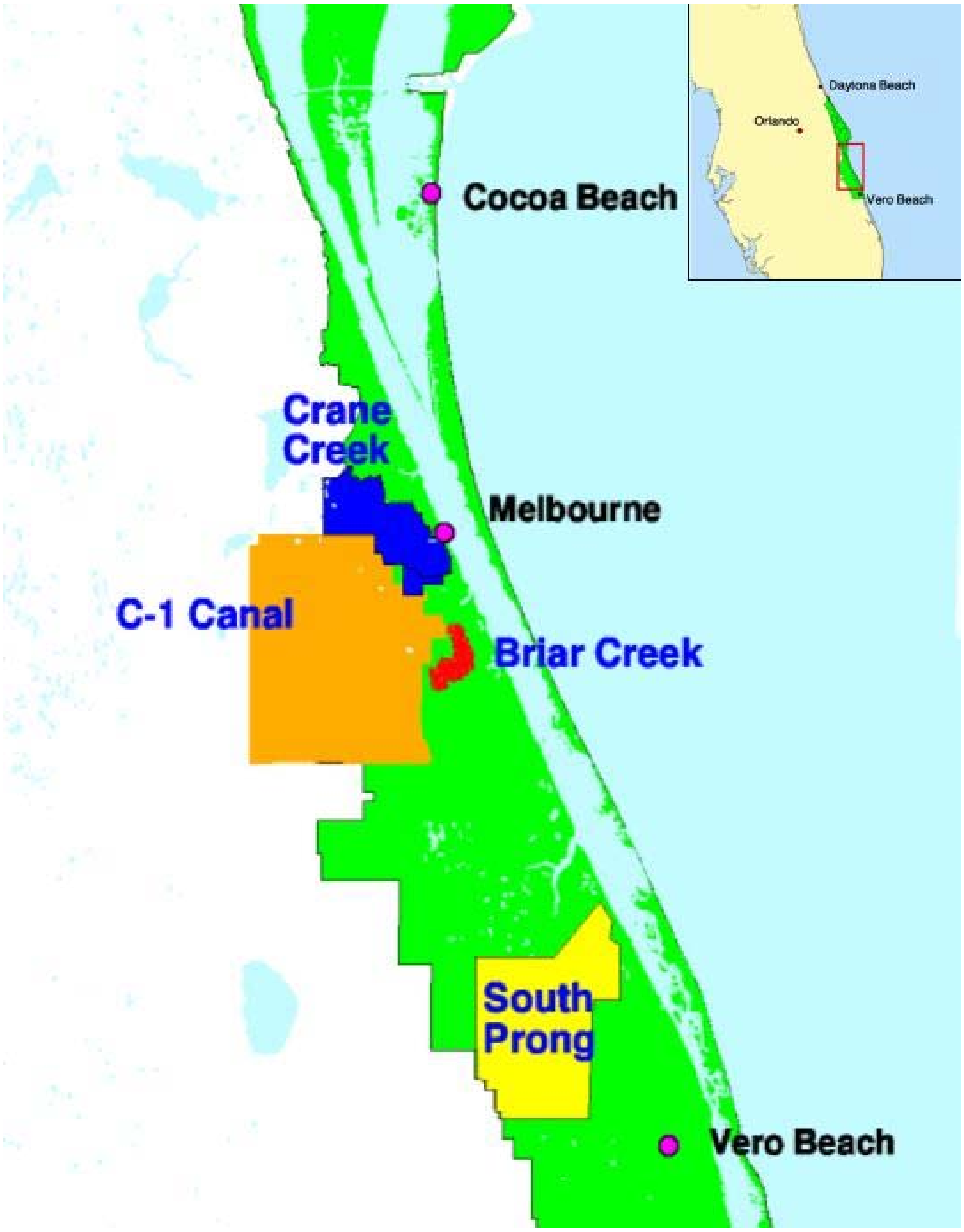

Figure 2. Cumulative annual loading: PLSM vs. Measured

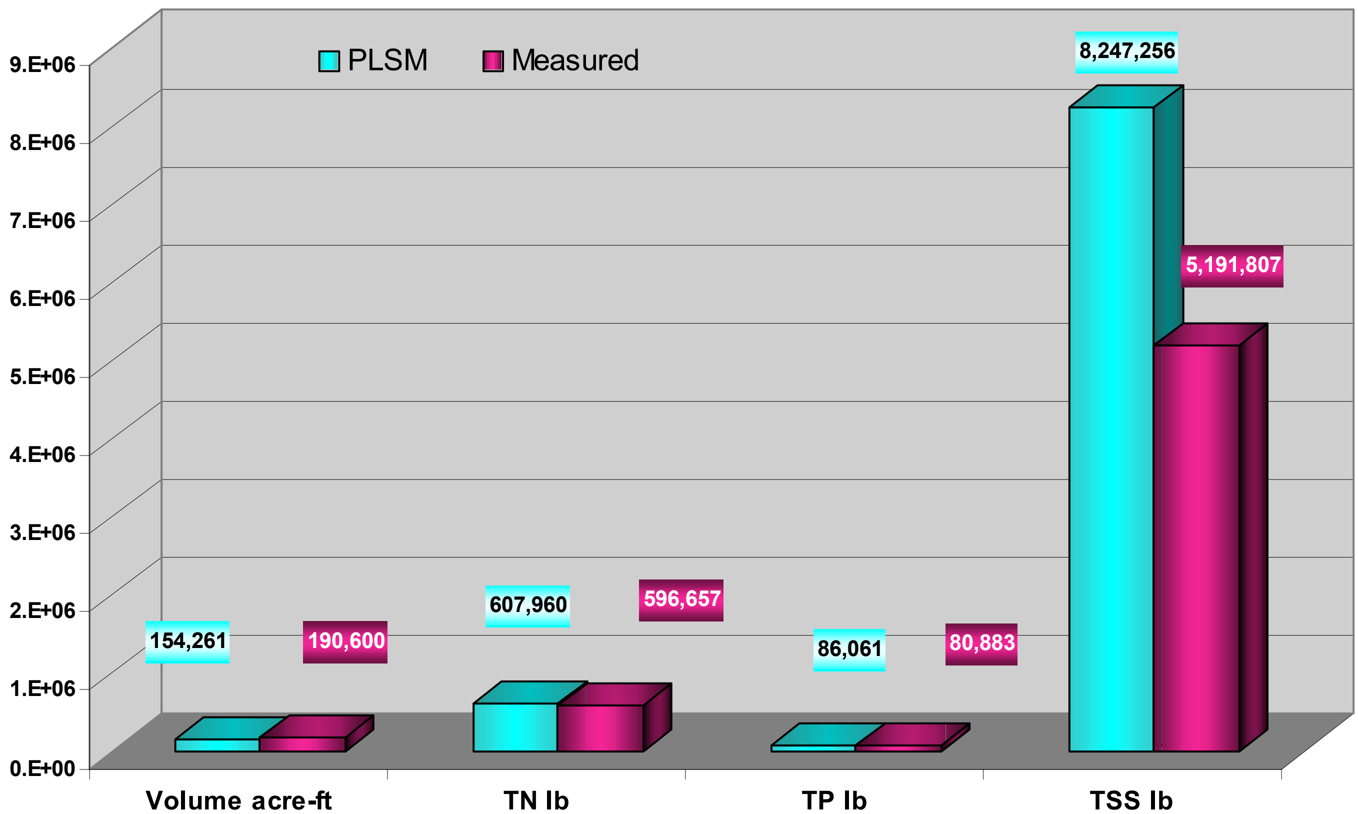

Figure 3. Cumulative absolute value of differences in loading: PLSM vs. Measured

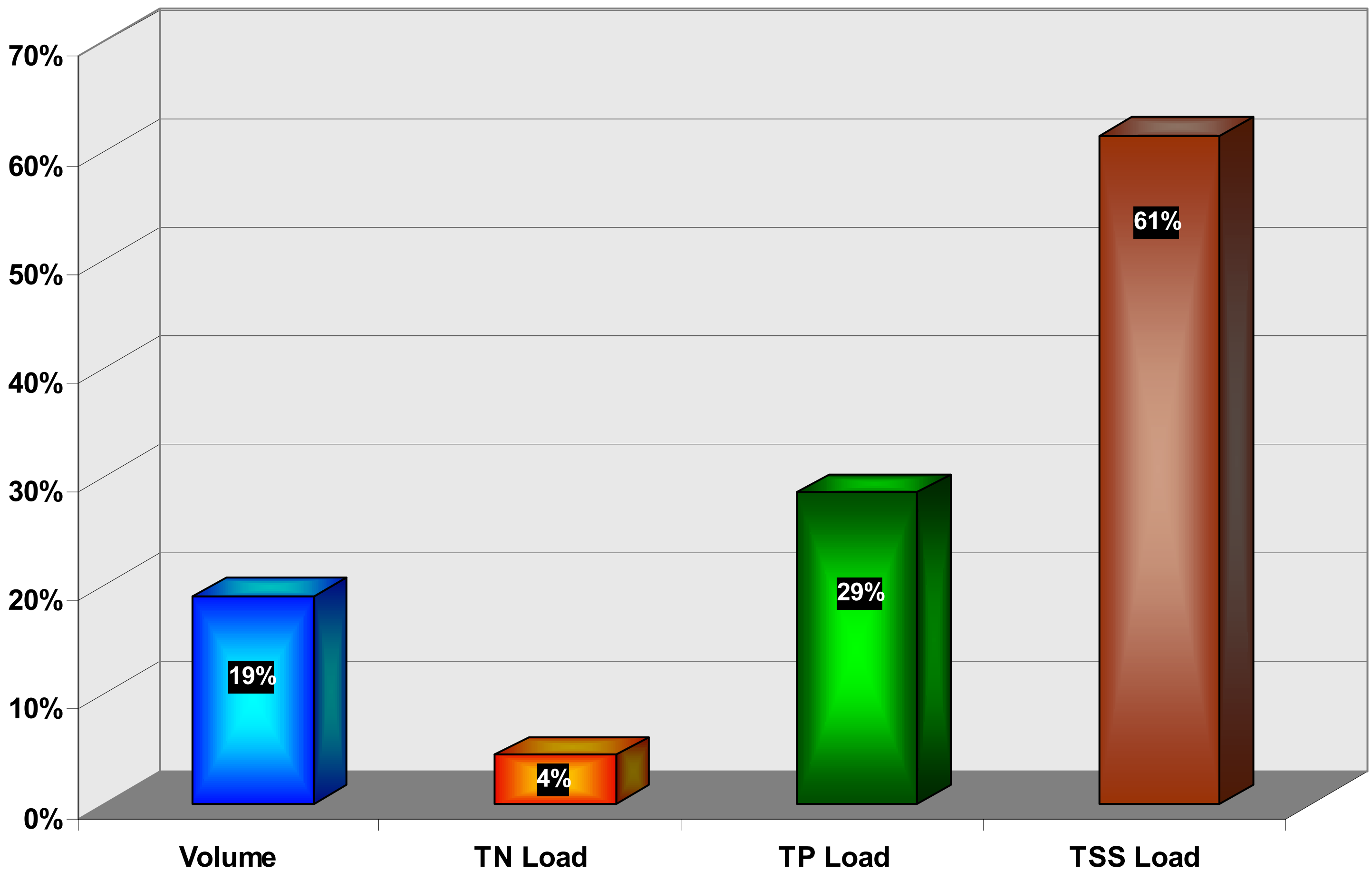

Figure 4. Cumulative annual loads: PLSM vs. Other Models