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Novel Concept for Modelling Nutrient Pollution in Upper Uma Oya Catchment in Sri Lanka

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ABSTRACT. *The main aim of the study is to address the problem of nutrient pollution (Nitrogen-N and Phosphorus-P) at the scale of catchment. In view of this, a simple model called TOPCAT-NP based on the existing model TOPCAT-N was developed with a minimum set of calibration parameters. Physically based Erosion Productivity Impact Calculator model and the export coefficient approach were used to study the processes of nutrient transport. The new model TOPCAT-NP is capable of simulating hydrological processes, N leaching and soluble and sediment attached P transport. This model allows a direct and dynamic link with Geographical Information Systems. TOPCAT-NP is based on the Minimum Information Requirement approach, which attempts to use a simple, justifiable model structure with a low number of key parameters for application to catchment planning. According to the results obtained, the TOPCAT-NP was proven to be a promising model that can work under limited catchment information. The developed TOPCAT-NP model was applied to Upper Uma Oya catchment in Sri Lanka to evaluate the surface water quality and the water quality changes with various land use/cover scenarios. The results revealed that the agricultural land use contributes extensively to the surface water quality deterioration in the studied catchment while forests contribute the least. Well-managed tea has very little contribution to the surface water pollution.*

INTRODUCTION

Land management and its impact on environmental quality can be addressed by using a suitable set of tools combined with a proper understanding of the landscape processes. Various analytical tools and experimental designs have been adopted to date and significant progress has been made in measuring and analysing on-site processes. However, the question remains whether our knowledge on a point or a plot within the landscape is adequate to represent the complicated landscape processes (Beven, 1989; Beven, 1996; Refsgaard, 1996; Kessel and Wendroth, 2001). Hydrological and water quality modelling must address the issue of scale. Scaling-up of point or plot scale process to management scale (small catchment or river basin) should be exercised with a great caution having a proper understanding of the biotic and abiotic processes occurring across the landscape.

This study was aimed at studying the hydrological and nutrient transport processes using one dimensional physically-based models and then coupling the knowledge with the simple modelling concepts to derive a reasonably simple and efficient modelling tool for catchment management. To achieve this aim, physically based Erosion Productivity Impact Calculator (EPIC) field scale model (Williams, 1995) was chosen for detailed analysis. A

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more simple export coefficient modelling approach (Beaulac and Reckhow, 1982; Johnes and O'Sullivan, 1989; Johnes, 1996; Johnes *et al.*, 1996) and TOPCAT Minimum Information Requirement (MIR) model (Anthony *et al.*, 1996; Quinn *et al.*, 1996, 1999) was also selected to be tested in this study. The MIR modelling concept (Anthony *et al.*, 1996) is considered as a parsimonious modelling approach which uses a simple but justifiable model structure to simulate hydrology and nutrient transport on the basis of available data, that include the key transport mechanisms believed to be occurring in reality. MIR models are basically the functional representations of complex physically-based models and rely on few key parameters which are sensitive to the spatio-temporal variability within the catchment.

The objectives of this study were to: i) identify the MIR model TOPCAT-NP and its applicabilities for nutrient pollution studies at the catchment scale (in the main); ii) study the EPIC and Export Coefficient approaches and the use of these concepts in MIR modelling and iii) apply the developed model to Upper Uma Oya agricultural catchment to observe the behaviour of the model with various land use/cover scenarios.

METHODOLOGY

Modelling background

The EPIC model runs were carried out for various land use, soil and slope conditions to develop relationships between nutrient transport and the hydrological flow paths at one dimensional scale. It also explored the possibility of deriving nutrient export coefficients from the model output. The export coefficient approach was then studied and the feasibility and limitations in the approach were identified for MIR nutrient modelling. Finally, the knowledge obtained from the two modelling techniques was integrated to develop TOPCAT-NP catchment scale water quality model.

TOPCAT-NP Minimum Information Requirement (MIR) model

Existing TOPCAT-N (Anthony *et al.*, 1996; Quinn *et al.*, 1996, 1999) model was used as the basis for developing the TOPCAT-NP. The hydrology and NO_3-N transport components of the TOPCAT-N was used in the model. Hydrology was altered to include the critical source area contributions to stream P levels. The soluble and sediment attached P transport components were incorporated to the model. Soluble P loss in the surface runoff at the initial day of simulation was calculated with the same formula used in EPIC (Williams, 1995) and AGNPS (Young *et al.*, 1995). This is a function of available P in top one cm of soil, the amount of surface runoff and extraction coefficient for P. The sediment attached fraction of P was calculated with the help of the amount of soil loss per unit width of hillslope. The amount of soil loss per unit runoff and unit width of hillslope was taken from another MIR model called MIRSED (Brazier *et al.*, 2001) to calculate the sediment attached P.

The developed model was applied to upper Uma oya catchment in central Sri Lanka to simulate the hydrological and nutrient transport characteristics of the catchment. The upper Uma oya catchment is located within the upper Mahaweli catchment area. There were no nutrient time series available for the catchment. Hence, water samples were collected at weekly intervals for eight months and analysed for NO_3-N and PO_4 using a portable photometer. Rainfall and flow data were obtained from the data archives of the Mahaweli Authority of Sri Lanka. Continuous daily flow data were available at the catchment outlet from January 1996 to August 2000. This data were adequate to calibrate and validate the hydrological module. This model was also used to study the changes in land use/cover in hydrology and nutrient mobilisation in the catchment. The following scenarios were tested in the modelling exercise.

a) Scenario 1 - The entire upper Uma oya catchment is forest only.
b) Scenario 2 - The entire upper Uma oya catchment is tea only.
c) Scenario 3 - The entire upper Uma oya catchment is vegetable only.

RESULTS AND DISCUSSION

Running the EPIC physically based model for various combinations of crop, soil, land, weather and fertiliser conditions helped to understand the N and P mobilisation and their interactions with the hydrology. The model provided a good background to test typical scenarios and to determine underlying patterns of N and P losses (*e.g.*, Long term linear trend in cumulative N and P fluxes). These relationships were approximated by more simple functions; and were used in the MIR modelling approach.

TOPCAT-NP Minimum Information Requirement (MIR) model

The TOPCAT-NP model was programmed on an Excel spreadsheet. It facilitates to keep the model simple and is easily understood by the user. Since the Excel works together with Visual Basic applications, it is a good user interface. The model structure was arranged in columns. It contains data input columns, hydrological module, nitrate and phosphorus modules in a sequence. The interactive calibration buttons attached to the parameters are centrally located in the sheet (Fig. 1). The interactive parameter buttons are useful to change the parameter values within a realistic range to obtain a proper calibration. The output graphs located adjacent to the buttons immediately reflect the model response to parameter change. This facilitates easy and fast calibration and the uncertainty in the output due to direct visibility of parameters. The output can be stored in another worksheet for later use.

TOPCAT-NP model organisation provides the user to get a knowledge about the model and the way it works, through the model structure, data sheets and calibration process. The model provides the outputs of flow, NO_3-N, soluble PO_4 and total P at the catchment outlet in required time steps. Importantly, the model can make predictions on any time step if the input data available at the required temporal resolution. The TOPCAT-NP contains only 14 calibration parameters (Fig. 1). The interactive calibration approach of the model is simple and efficient as the results are immediately visible. The effect of each model parameter on the final output presented in a transparent way.

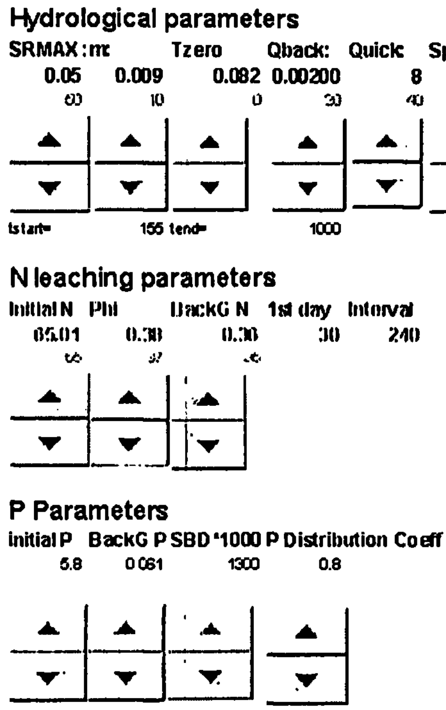

Fig. 1. TOPCAT-NP interactive calibration profile.

Hydrology and water quality assessment of upper Uma oya

Flow data of 1996 were not used in calibration due to irregularities in measurements. Instead, 1997 observed flow data were used. Fig. 2 presents the calibration results of the hydrological module at the upper Uma oya catchment outlet. The model can closely simulate the observed pattern of flow. The major hydrograph peaks during the rainy season produce an excellent agreement with those of the measured. With the calibrated parameters, the model overestimates the flow during the 98/99 rainy season. Storm flow largely dominates the stream flow and therefore, individual storm events produce a sharp recession immediately after the rainfall events. Fig. 3 shows the pattern of NO_3-N transport in the catchment from Jan. 1996 to Aug. 2000. Annual cycles are prominent in 97/98, 98/99 and 99/00 hydrological years, however, different leaching rates are observed. The sharp downward peaks occur due to dilution of NO_3-N during high flow conditions. The NO_3-N simulation for the calibration period is presented in Fig. 4. The correlation coefficient obtained for the measured and simulated NO_3-N was 0.73, which indicates a good correlation between the two variables. The calculated Nash efficiency (Nash and Sutcliffe, 1970) for the calibration period was 52.7%. According to the Fig. 4, the recession of NO_3-N with the recession limb of the annual flow hydrograph is very prominent.

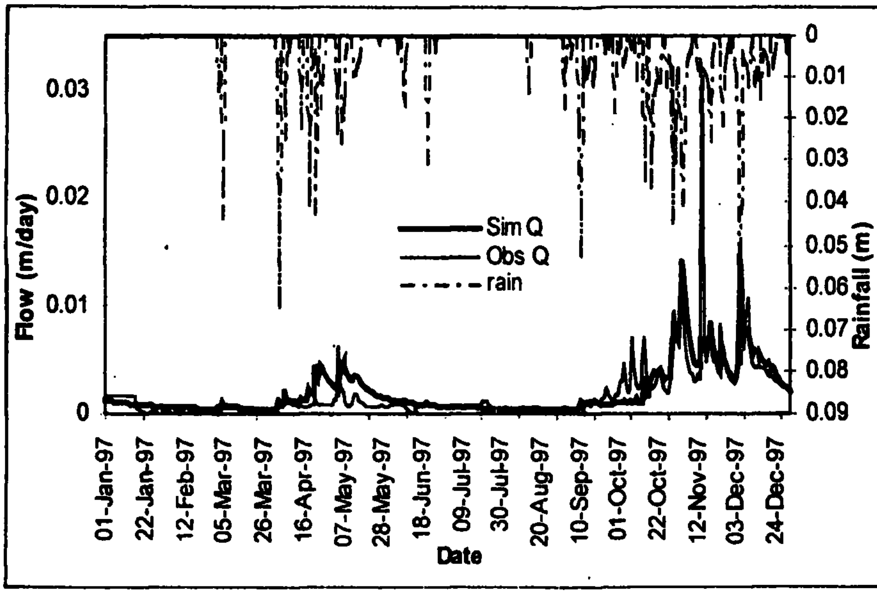

Fig. 2. **Rainfall and simulated and observed flow hydrographs for calibration period at Welimada gauging station (Jan. 1997-Dec. 1997).**

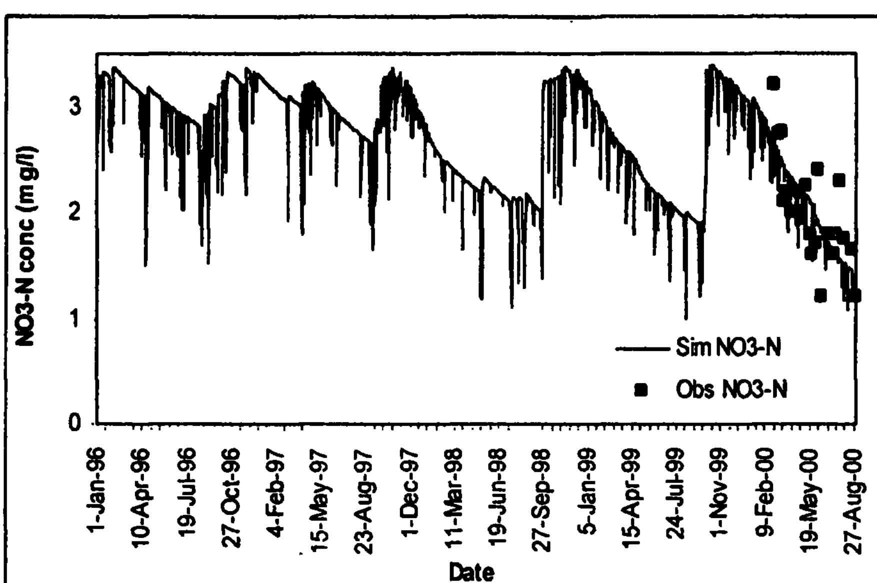

Fig. 3. **Annual pattern of NO_3-N at the catchment outlet (Jan. 1996-Aug. 2000).**

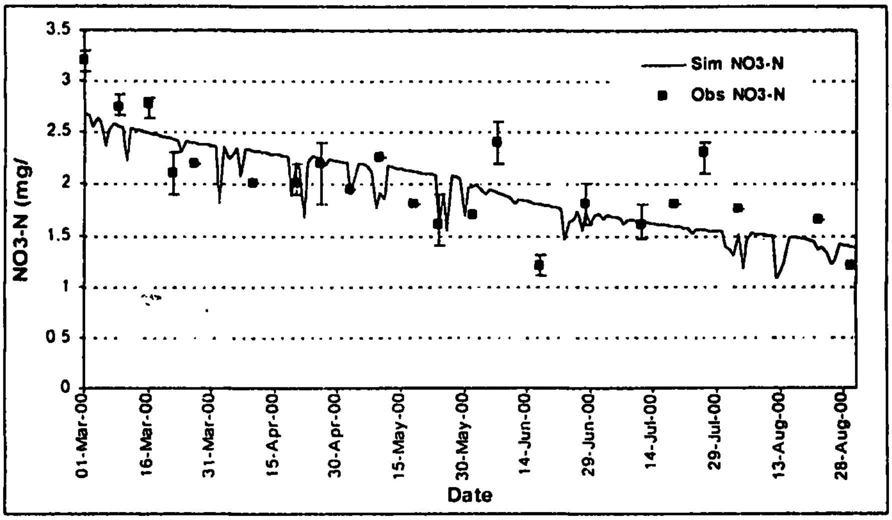

Fig. 4. Calibration results of NO_3 module at the catchment outlet (Jan.-Aug. 2000).

The outcome of the soluble PO_4 module calibration is presented in Fig. 5. The Red Yellow Podzolic (RYP) soils of the up country and intermediate zones that are occupied by exotic vegetables including potato, are rich in P and K. The Olsen P levels of these soils range from 100-250 ppm (Lathiff and Nayakakorale, 1993) which are far above the breakpoint Olsen P level in the soil to trigger active leaching (60 ppm). RYP soils are distributed in areas receiving high rainfall above 1625 mm and are subjected to rapid leaching. Favourable soil texture of sandy loam or sandy clay loam of these soils along with steep topography would help to transport a significant amount of P in subsurface flow paths. Therefore, it is possible to assume that leaching has a significant contribution towards P in the streams in this catchment.

Sudden peaks in observed PO_4 may be a result of localised events such as point source discharges. The farmers in the lower region of the catchment irrigate their rice and vegetable fields with stream water and redirect the excess water back to the stream. In general, this water is extremely rich in sediments and could be equally high in P as the sediment is derived from P rich soils. This also could be a reason for suddenly elevated soluble PO_4 in stream water.

Hydrology and water quality with changing land use/cover

The pattern of stream discharge at the catchment outlet (Fig. 6) did not change drastically when the catchment land use/cover changes from mixed to forest, tea or agriculture. The total flows generated during the modelling period are 2.58, 2.92, 2.83 and 3.16 m (flow has been simulated as a height) for forest, tea, agriculture and mixed land use, respectively. These values indicate that there were changes in flow with different land use conditions, although the changes are relatively small.

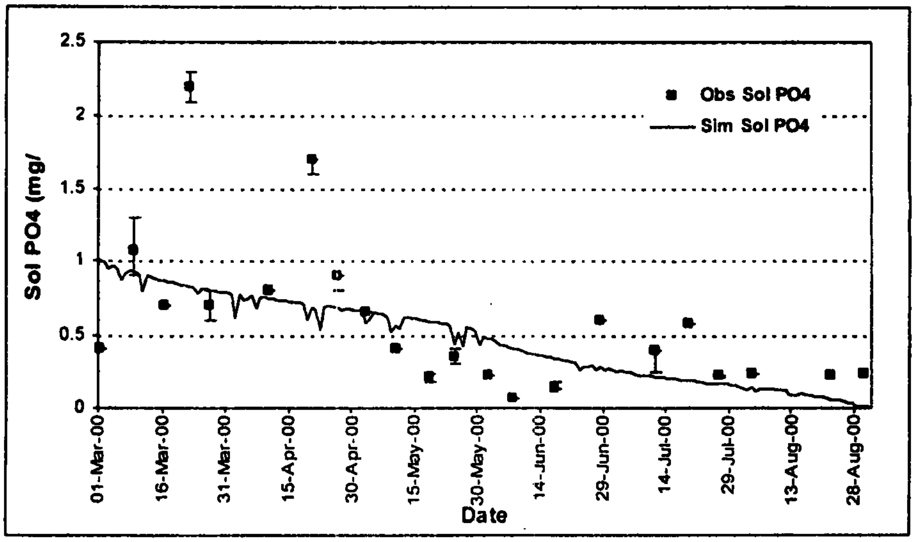

Fig. 5. Calibration results of PO_4 module at the catchment outlet (Jan.-Aug. 2000).

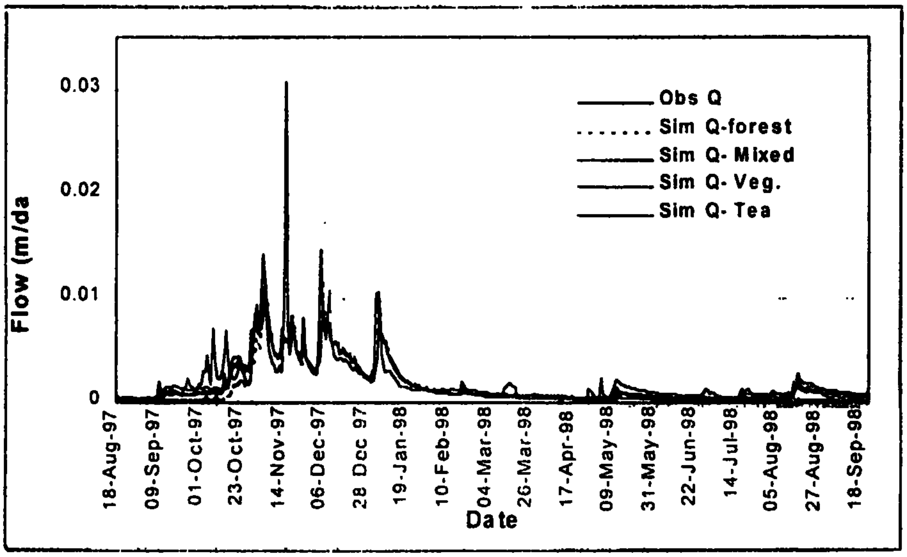

Fig. 6. Observed and simulated flow under three land use/cover scenarios.

The effect of land use on stream NO_3-N transport is highly significant (Fig. 7). The simulated NO_3-N becomes maximum under all-agriculture scenario; though the concentrations do not exceed the WHO limit of 10 mg/l for drinking water. The lowest NO_3-N concentrations appear with all-forest scenario. NO_3-N generation is relatively low if the entire catchment is converted to tea. All-vegetable scenario generates the highest soluble PO_4 in streams (Fig. 8).

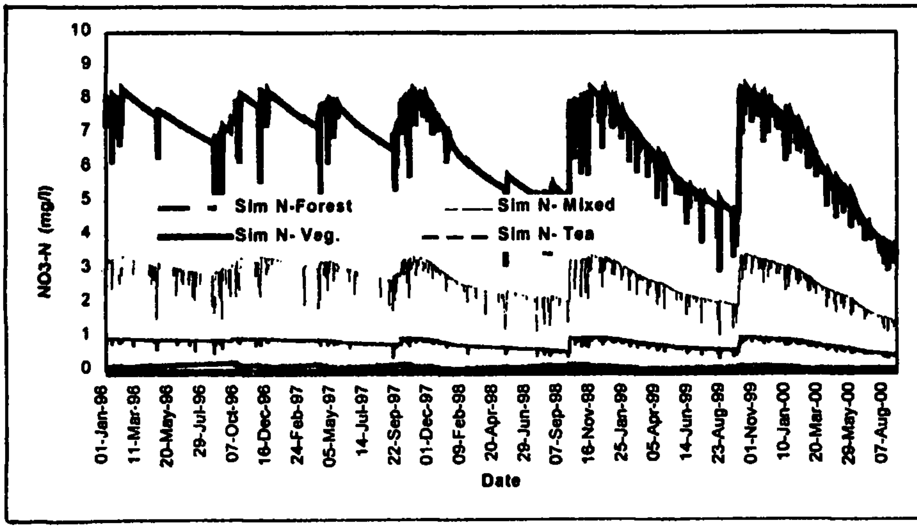

Fig. 7. Simulated NO_3-N under three land use/cover scenarios.

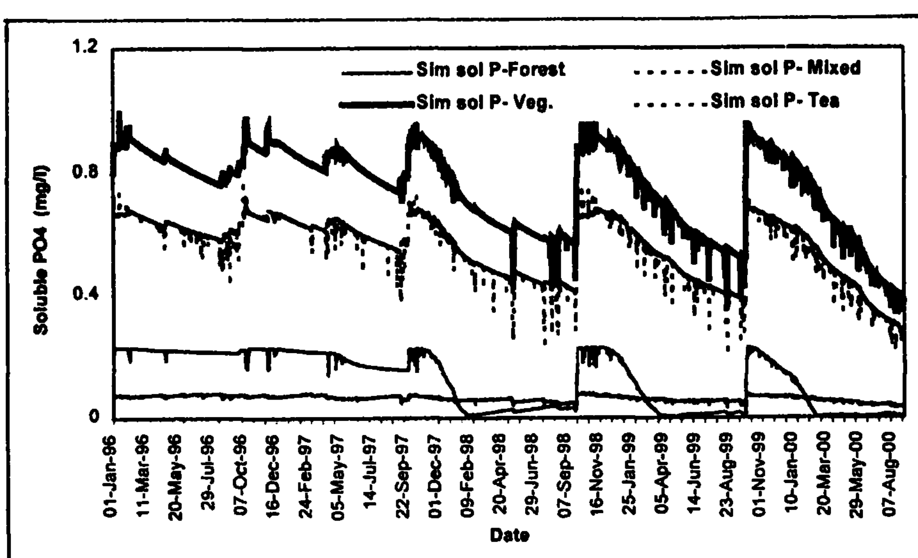

Fig. 8. Simulated PO_4 under the three land use/cover scenarios.

Interestingly, tea produces the lowest soluble PO_4 that is always lower than that of a catchment under forest. This may not be generic and may be a result of slow decomposition of leaf litter under low temperature conditions and release of P during this process. Though, it was not measured the particulate P contribution from tea lands can be higher to that of forests due to fertiliser applications and soil erosion. The result does demonstrate the impact of the change. However, one must accept that the parameters and the P modelling need more work to identify all the mechanisms and processes that govern the P mobility.

CONCLUSIONS

The TOPCAT-NP model consists of a simple structure and minimum number of key parameters, and requires relatively less catchment information for its calibration. Therefore, it can successfully be used in catchments where information is scarce. The basic theory behind the TOPCAT-NP nutrient transport components is closely associated with that of the export coefficient approach. In this regard, this model is complementary to the existing export coefficient approach, which works on an annual resolution. The daily or sub daily resolution of the output of TOPCAT-NP provides important information on storm affected/seasonal variations of hydrology, NO_3, soluble and particulate P transport.

Land use/cover scenario analysis provides an insight to the effect of land use/cover changes on flow and surface water quality. With the parameters that are sensitive to land use/cover and management practices in TOPCAT-NP, the model can potentially simulate stream flow and nutrients under various land use/cover options. The model results may be used as a guideline to identify the most suitable land use options and management criteria. However, the user should be well aware of the uncertainty associated with the parameters and its propagation to the final model output.

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