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A tutorial modelling approach to explain the reflexes in the system dynamics of the Batticaloa Lagoon in response to discharge from irrigation tanks

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Abstract:
Any effort to managing the Batticaloa lagoon well should begin with understanding its dynamics as a key contributor to flood mitigation and control. Of particular concern in these regards are the inputs from major and minor irrigation tanks (that are connected to the lagoon) that disturb the natural stability of the Batticaloa Lagoon. Understanding the interconnected mechanics of the tanks and the lagoon could be enhanced by the exploration of the processes through conceptual/mathematical simulation models. In this respect, a tutorial simulation model: ***TIL 1.0*** *was developed using in the STELLA® v7.03-modelling platform to imitate the interconnectivities between and irrigation tanks and Batticaloa Lagoon. The Model* ***TIL 1.0*** *presents an easy to way to simulate different processes of the problem of concern and generate various outputs such as water raise in lagoon, water levels, excess water in lagoon, salinity drop, chance of flooding, and Bar-Mouth condition/s. The unique aspect of the* ***TIL 1.0*** *is that it is less technical savvy, and, provides the opportunity to non-scientists (i.e. administrators and bureaucrats) to understand the lagoon system in a logical manner and consequently take sustainable decisions in managing the said system.*

Key words: Bar-Mouth, Conceptual Model, Modelling, Scenarios, Simulation Model

1. Introduction

Modelling is an essential process in understanding systems of all kinds [3], and, modelling in general is most valuable and cost effective tool in decision making for any system since it caters spatial and temporal understanding of that particular system. Models can be applicable to understand any cultural/natural/economical/social phenomena in the world. The modelling exercise, performed based on the natural phenomenon, can be termed as Environmental

Modelling which can be defined as the simplification of the known real world or virtual processes to understand its function and interrelationship between the known components of that processes and/or to test and predict the future plausible scenarios. Environmental models enhance our understanding of environmental systems, facilitate the prediction of future outcomes, and pave the way to control/manipulate the few components to maintain the integrity of natural system. This exercise applies focuses on modelling the Batticaloa lagoon's dynamics to understand its system properties/processes in response to a perturbation *i.e.* discharge of extra fresh water from the irrigation tanks.

1.1. Composition and functions of Batticaloa Lagoon

Batticaloa Lagoon is the largest one of the three lagoons in Batticaloa district and takes an area of 115 Km^2, and is 56 km in length [5], extending from Pankudaweli in North to Kalmunai in South and has an average depth of 4.8 meters [1]. Since there is rich biodiversity, the lagoon is an important socio-economic supporting mechanism for the people living in its peripheries and act as an important groundwater-recharging source in its peripheries [10]. Further, in the southern parts of the lagoon where salinity is zero, the lagoon water is also used for the irrigation. Catchment area of this lagoon include (seasonal) rivers, major and minor irrigation tanks, and runoff from the adjacent land mass. About eight seasonal rivers drain into the lagoon. All such rivers originate a catchments area of about 1593 Km^2 [6]. Since this lagoon communicates with sea through two bar mouth *i.e.* Palameenmadu bar mouth and Koddaikallar bar mouth, this could be classified as a chocked lagoon [2]. Both bar mouths of the Batticaloa lagoon are opened by human interventions in most instances. The Palameenmadu bar mouth is cut open by the Road Development Authority when the water level raises under the Kallady Bridge, by 2.75 ft Mean Sea Level [6].

However, the Batticaloa Lagoon's state of natural stability is often perturbed by anthropogenic and natural influences. Such perturbations are constructing bridges across the lagoon, dumping the industrial and municipal wastes, influences on bar-mouth, re-vegetation within the lagoon, discharge of extra freshwater into the lagoons from the tanks and Tsunami etc. Some perturbations had been studied by several authors on the Batticaloa Lagoon. The influence of bridges on hydrology of lagoon and spatial structure of lagoon had been analysed through a model N-BIOL and according to this model, it was found out that the unplanned bridges act as partial impoundments and ultimately reduce the spatial extent of some parts of the lagoon by the increased sedimentation [11]. Further, bridges across the lagoon have a teleconnection with the bar-mouth mechanism of Batticaloa lagoon and this was analysed through a conceptual model BIOB 1.2 and this findings elaborate that the unplanned bridges impact on natural bar-mouth functions *i.e.* closing of the bar mouth in the dry season and its opening in the wet season closing period [4]. The effect of tank discharge also has been studied through simulation modelling approach [12] and the study presented a simulation model UnTil and revealed several impacts of Unnichchai Tank on the lagoon.

The present modelling exercise also exaggerates on the impacts of irrigation tank discharges on the Batticaloa Lagoon. Some authors in other parts of the world already have engaged in analysing the effect of extra freshwater inputs, especially from irrigation tanks into the lagoons [7] analysed such effect on the lagoon in southern Sri Lanka. Inputs of irrigation tanks in the lagoon system have several effects even to the biota of the lagoon ecosystem. The organisms in the lagoon are adapted to the prevailing environmental conditions of the lagoon or to the adjacent sea. However, input of extra freshwater into the lagoons would render them unsuitable to existing aquatic species [7].

The Batticaloa lagoon has also been in connection with several minor and major irrigation tanks. About twenty minor and three major irrigation tanks discharges the water into the lagoon. Major tanks are Navakiri tank (which have 70 square miles catchment area and drains in southern part of the lagoon), Unnichchai tank (catchment area is 106 square miles) and Rugam tank (catchment area is 35 square miles). Both Unnichchai and Rugam tanks drain in northern part of the lagoon [12]. However, the inputs from all these tanks are seasonal. Present study focuses on the reflexes of Batticaloa Lagoon in response to discharges from all three major tanks and it uses simulation-modelling approach in STELLA modelling platform.

2. Materials and Methods

2.1. Development of a Simulation Model

A conceptual model was developed in a flowchart manner (Fig 1) based on the understanding of the interconnectivity of the three major tanks and Batticaloa lagoon. This model uses several different assumptions to understand the system easily. Assumptions of this conceptual model are listed as follows.

1. *All the water released from the tanks reach the Batticaloa lagoon.*
2. *The catchments of Batticaloa lagoon consist only three major irrigation tanks.*
3. *Batticaloa lagoon communicates with sea only by one bar mouth.*
4. *Mechanism of bar mouth is only influenced by natural functions without any human interventions.*

Based on the conceptual framework (Fig 1), a simulation model was developed in STELLA v7.0.3 modelling platform. STELLA® is widely used among the environmental scientist and/

or system scientist to develop the models of different needs and it offers a practical way to dynamically visualize and logically construct the models of complex systems (www.hps-inc.com). In Stella platform, there are four types of building blocks such as stocks, flows, converters, connectors and a space saving device i.e. decision process diamonds (Fig 2) and these can be used to build a model.

2.2. Calculating the total discharge from tank to Catchments of Batticaloa Lagoon

Monthly spill discharge and issued water volume from each tank were summed to calculate the total runoff from all three tanks in "Whole Inputs" converter and this converter is connected to stock (Catchment to lagoon) through flow (Fig 3, Sector 1 & 5). In addition to this, forecast of all these tank discharges were added within decision process diamond (DPD).

$$C(t) = C(t - dt) + (IC - IF) * dt \qquad \text{Eq. 1}$$

Where; **C**-Catchments to lagoon

IC-Inflow to catchments

IL-Inflow to lagoon

2.3. Calculating the raise of water level in Batticaloa lagoon by the input of tank waters

The increase of water level only by the influence of tank water can be calculated by dividing the volume of inflowing water by the total area of the lagoon. Here the increase is named as "Water raise" in the model (Fig 3, Sector 1).

$$\text{Water\_raise} = (\text{inflow\_to\_lagoon})/\text{Lagoon\_\_area} \qquad \text{Eq. 2}$$

2.4. Calculating the Excess water in the lagoon

Excess water means that the water that exceeds the water holding capacity of the lagoon. Hence, to calculate this parameter the water holding capacity of the lagoon (WHC) and net water volume in the lagoon (NWV) are needed. In this model, NWV is calculated using following equation.

$$NWV = LPV + \text{inflow\_to\_lagoon} + DRF + \text{Forecasted\_Rain} \qquad \text{Eq. 3}$$

Where; LPV- Existing Volume of water

DRF- Direct rainfall onto lagoon

Forecasted_Rain- Forecasted monthly rainfall

Existing Volume of water (LPV) in the lagoon is calculated by multiplying the lagoon present depth (water depth) and the area of the lagoon, as shown by following equation.

$$LPV = \text{Present\_depth} * \text{Lagoon\_area} \qquad \text{Eq. 4}$$

Further, direct rainfall onto the lagoon (DRF) and forecasted rainfall were also added to this equation. The DRF was calculated as follows.

$$DRF = \text{Monthly\_Rainfall} * \text{Lagoon\_Area} \qquad \text{Eq. 5}$$

The water holding capacity of the lagoon (WHC) was calculated by multiplying the lagoon original depth and lagoon area. The equation behind the WHC converters is as follows.

$$\text{WHC} = \text{Lagoon\_\_area} * \text{Lagoon\_depth} \qquad \text{Eq. 6}$$

Excess water was calculated by a logical function. In the "Excess water" converter, the following equation was added.

$$\text{Excess water} = \text{IF(NWV} < \text{WHC)THEN(0)ELSE(NWV - WHC)} \qquad \text{Eq. 7}$$

In this section of model (Fig 3, Sector 3), another parameter is "Flood chance", which indicates actually the period in which the risk of flooding is high. The equation for Flood chance is defined as a logical function, in which it is set to elicit a dummy non-zero constant (usually one) in response to excess water when Bar-Mouth is closed.

2.5. Determining the effect of tank input on the bar mouth mechanism

The all three tanks input may also have some effect in the bar mouth mechanism. In order to determine the bar mouth condition, water level, (or water depth) is needed. Hence, the water level is determined by dividing the net water volume (NWV) by lagoon area (Fig 3, Sector 4). Hence, in the "Water level" converter, the following equation is added.

$$\text{Water\_level} = \text{NWV/Lagoon\_\_area} \qquad \text{Eq. 8}$$

Now the bar mouth condition is determined by a logical function which sets, for the plotting purpose, to elicit a dummy non-zero constant (usually 1) for open mouth phase and zero for closed mouth phase (This method of bar mouth representation was adopted from [8]). The non- zero constant results when the water level exceeds some level, *i.e.* very closer to the lagoon original depth else the number remain zero. The number one indicates that the bar mouth is opened and the number zero indicates bar mouth is in closed position. In this part of the model, "Present depth" converter is also added in addition to the "Water level" converter. This is to compare the effect of the tank input with that of the normal condition. Further, two switch converter is also added to control each parameters. The equation added in the "Bar mouth condition" converter is as follows.

$$\text{BC} = (\text{IF}((\text{WL}^* \alpha) + (\text{PD}^* \beta) > 3.8)\text{THEN}(1)\text{ELSE}(0)) \qquad \text{Eq. 9}$$

Where; **BC**-Bar-Mouth Condition
WL-Water level
PD-Present Depth
α - Tank water input switch
β – Normal Condition switch

2.6. Determining the effect on lagoon salinity

Salinity drop is the magnitude by which the salinity of the lagoon decreases. According to the following equation [9], when the influx water volume increases into the lagoon, salinity of the lagoon decreases.

$$C = \frac{L}{V} \qquad \text{Eq. 10}$$

Where; C- Concentration of salts in the lagoon
L- Load of salts in the lagoon
V- Volume of water in the lagoon

The decrease in lagoon salinity is determined by this of model (Fig 3, Sector 2), where in "Salt load" converter, a positive integer number is added with the unit of parts per thousand (ppt). In the "Salinity" converter, the following equation is added to calculate the decrease salinity. Finally, to calculate the salinity drop, output of "Salinity" is subtracted from "Salt load."

Salinity = (Salt_load * LPV)/NWV   Eq. 11

Salinity_drop = Salt_load - Salinity   Eq. 12

By integrating all sub parts of the models, the Model **TIL** (**T**ank **I**mpact on **L**agoon) version 1.0 was developed (Fig 3). TIL 1.0 has several sub models for various purposes such as for unit conversion, direct rainfall calculation, forecasting each of three tanks discharges and forecasting of monthly rainfall. This model requires inputs such as issued water volume and spill discharge from each of three tanks, which can be collected from Department of Irrigation. This data can be fed in Ac-ft unit, which is normally used by Dept. of Irrigation. Further, it needs district monthly rainfall to test some plausible scenarios and the rainfall data can be collected from regional meteorological department. The rainfall data can be fed in mm unit. This model gives six outputs such as water raise, excess water, water level, salinity drop, Bar-mouth condition, and flood chance.

The model was then simulated with only with Unnichchai tank discharge data (due to the lack of discharge data of other two tanks), correlation analysis was performed between, and tank total discharge and some output parameters. The Pearson product moment correlation coefficient shows mostly moderate correlation between tank discharge and output parameters such as rise in water level in lagoon ($r = 0.62$) excess water ($r = 0.7$) and salinity drop ($r = 0.607$). This analysis reveals some extent of the interconnectivities of tank discharge with lagoon dynamics.

3. Results

Exploration of the capacities of TIL 1.0

In order to test the capacities of the model, data on spill discharge and issued water volume of Unnichchai tank for six years (January 2000 to April 2006) was collected from the Department of Irrigation, Chenkaladi. This data was used to analyse the past condition of the lagoon in response to Unnichchai tank discharge into the lagoon. However, this will not reflect the actual past conditions, since the lack of data about other tank discharges, but will shows a trend of temporal change in all outputs and this can be used to test the model. The outputs of the simulations are described in forthcoming sections.

3.1. Rise in water level

According to Fig 4, the water raise in the lagoon was increased every year especially in the *yala* cropping season (April to September) to about 0.1 m. This is due to the release of water from the Unnichchai tank for cultivation purpose in the *yala* cropping period. Further, at the end of the year 2004 and 2005, the water level was increased by high magnitude i.e. at 2004 by 0.9 m and at 2005 by about 0.28m. This is due to the increased spill discharge from the Unnichchai tank.

3.2. Salinity Drop

Figure 5 indicates the salinity drop in the Batticaloa lagoon by the influence of the Unnichchai tank discharge and direct rainfall. According to this output, salinity drop, by the influence of Unnichchai tank water, is obvious during April to September (*yala* season); this trend is more or less same in all year except in the year 2005 and 2006. At the end and the beginning of the year 2004 and 2005 respectively, spill discharge was high from tanks and thus, it results in high magnitude of salinity drop in Batticaloa lagoon.

3.3. Excess Water

Figure 6 indicates the excess water in the Batticaloa lagoon by the influence of Unnichchai tank discharge and direct rainfall. This shows high volume of excess water is resulted in the beginning of the year 2005, and, there is insignificant volumes are produced in 2002, 2004 and 2006, only by the influence of Unnichchai tank discharge.

3.4. Condition(s) of the Bar-Mouth

In Fig 7, "At Normal Condition" legend indicates the normal bar condition of the lagoon while "At input of tank water" legend indicates the simulated bar mouth condition when Unnichchai tank water drains into the lagoon. According to this output, tank discharge changes bar mouth opening and/or closing period. In the year 2001, it induces early opening, while in 2004, and 2005, it induces late closing. In year 2002, it changes both opening and closing period.

4. Discussion

The present model gives a conceptual and mathematical idea to understand the responses of Batticaloa Lagoon in response to the extra freshwater inputs into it. In this respect, this model provides outputs such as rise in water level, salinity drop, water level, excess water, flood chance and bar-mouth condition, where flood chance and bar-mouth conditions are qualitative output, which gives only the periods of a year. These outputs explain the changes in some hydrological parameters of the lagoon, in response to tank discharge. The sudden changes in the Lagoon's hydrologic parameters have the adverse effect on its own biological system and affect the human dwelling adjacent to some parts of the lagoon. According to the figure 4, it is obvious that the raise water levels in the lagoon by the impacts of irrigation water and this could make feeding sites unavailable for many water birds in the surroundings of the lagoon [7]. Figure 5 shows the frequent reduction the salinity level of the lagoons that could convert the whole lagoon or particular part of lagoon, which is geographically isolated or isolated by constructing bridges, into freshwater aquatic system, which then leads to the migration of biota in that particular locality. The organism which have broad spectrum of salinity tolerance will only survive while others which have narrow spectrum of salinity tolerance will migrate out of that area or die off.

The figure 6 shows the variation in the excess water, that exceeds the water holding capacity of the lagoon. This excess water itself is the cause for flooding in the surrounding area, especially when the bar mouth is closed. This flooding is possible during the rainy season (North-East Monsoon period) and frequently in Sathurukkondan, Eachantheevu, and Pankudaweli experiences flooding in these periods. The risk flooding in these areas are associated, in addition to excess water, with other factors such as encroachment of the peripheral wetlands or modifying their drainage to lagoon and constructing the bridges across the lagoon with low flow of natural water. The Figure 8 explains how the wetland encroachment and constructing unplanned bridges are associated with flooding, in particular part of the Batticaloa Lagoon. This anthropogenic factors, act as a barrier, during rainy season, for the spreading of water into their peripheral wetland and to other part of the lagoon, thus flash flooding is resulted to the human settlement area. Further, this flooding ultimately results the erosion of lagoon bank and this erosion can be observed in Pankudaweli, where 500m (inland) X 1000m (lagoon shoreline) area is eroded [6]. Figure 7 compare the bar mouth condition at normal situation and when tank water discharges into the lagoon. Bar mouth of a lagoon, usually has a rhythmic process *i.e.* closing in dry season and opening in the wet season of every year [4]. The elapsed time between complete closing of bar mouth by the sedimentation and its opening is influenced by the input of water into the lagoon from various sources.

The above outputs were obtained only with Unnichchai tank discharge data and thus the real situation could be much deviated than what explained above. However, the simulated outputs reflect how tank discharges have profound impact on Batticaloa Lagoon's system dynamics, its biota, and surrounding human dwellings. In order to get most reliable data, it is must to incorporate discharge data of all three major irrigation tanks. The effects or changes observed in the model outputs will be enormous if all other tanks discharges are integrated in this model and will results in drastic changes in the lagoon, which ultimately adversely influence on the existing biotic community in the lagoon and on surrounding human settlements.

Though the model TIL 1.0 was developed based on the previous model UnTIl [12], it has advantages beyond the UnTil. Unlike UnTil, it uses the three major tanks, so that it gives better understanding of the perturbation on lagoon by the tank discharge. Further, it uses forecasting techniques, unlike previous, to forecast the future values of the tank discharges and the monthly district rainfall, so that it facilitate to test plausible scenarios, with regard to the problem of concerned. Unlike the previous model, the present model has unit converter in itself, thus it can accept the inputs in familiar units, such as Acre-feet (Ac-ft) for tank discharge and millimetre (mm) for rainfall. Moreover, the model TIL 1.0 is capable to test different plausible scenarios with the future forecast of discharges of each tanks and forecast of district monthly rainfall.

In reality, hydrologic processes are much related with spatial attributes and but the STELLA model merely not enough to take correct decision about the spatial attributes of the system of concern. However, the present model can be further improved as 2D model that integrates both hydrological and spatial component of the system of concern and this can be archived with the incorporation of Geographic Information System and Remote sensing (GIS & RS) techniques. This proposed 2D model will further elaborate the reflexes in system dynamics in response to the adding of extra freshwater discharges into the lagoon and this will well facilitate the decision makers to travel in a correct path in their decision with low level of scientific background with regards to the hydrology of the Batticaloa lagoon and its catchments.

Beyond the scope of this modelling exercise, it is essential to touch an important criticism in the field of the modelling is that the most of the models constructed conceptually and/or mathematically based on the understanding of the natural phenomenon are mostly linear, but the system in nature in most time behave non-linearly or have more random events in its behaviour. As such, the next generation/s of this modelling exercise should aim at incorporating the element of unpredictability into this system so as to provide a comprehensive explanation of the dynamics concerned.

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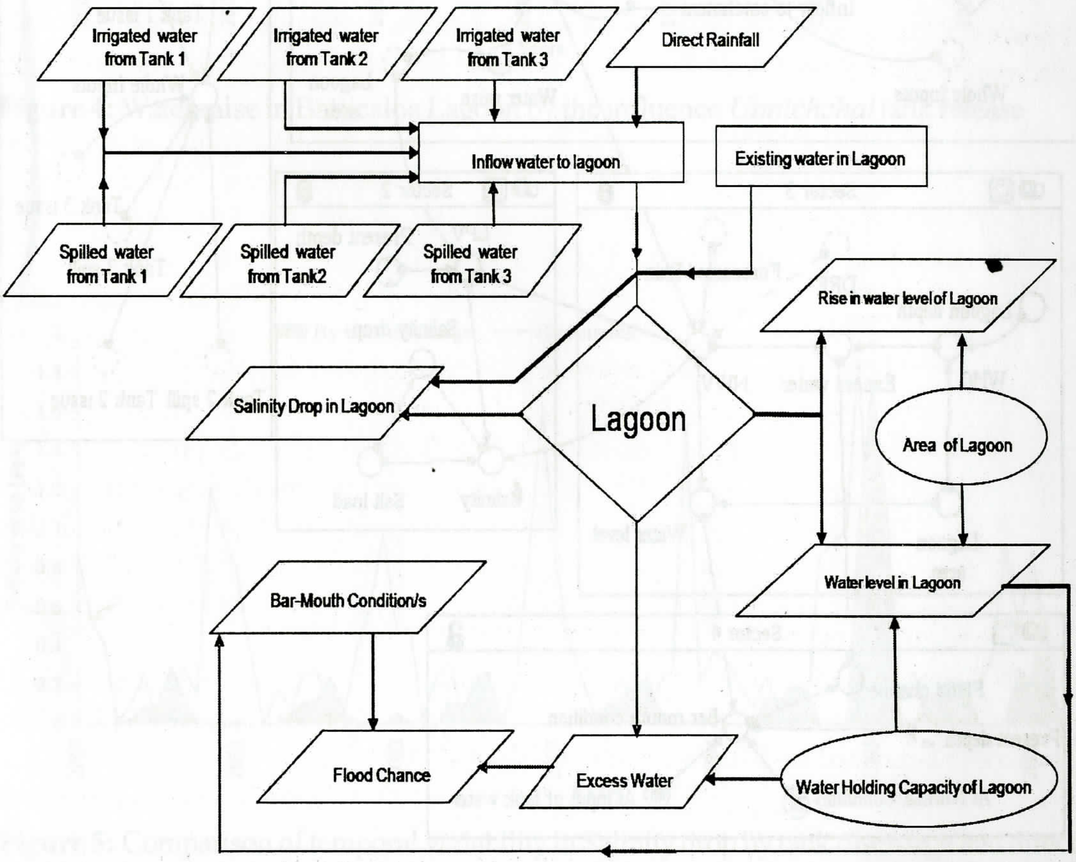

Figure 1: Conceptual model for the simplified hydrological system of Batticaloa Lagoon (Developed by Author)

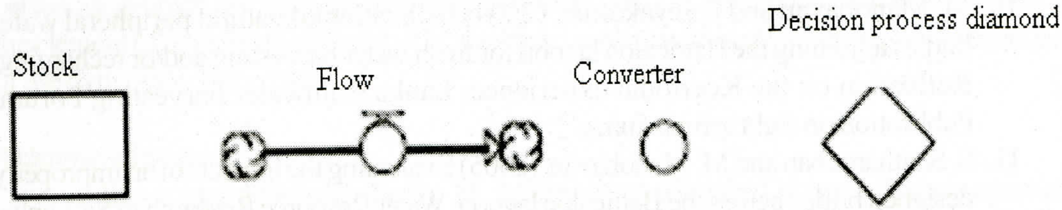

Figure 2: Building blocks in Stella

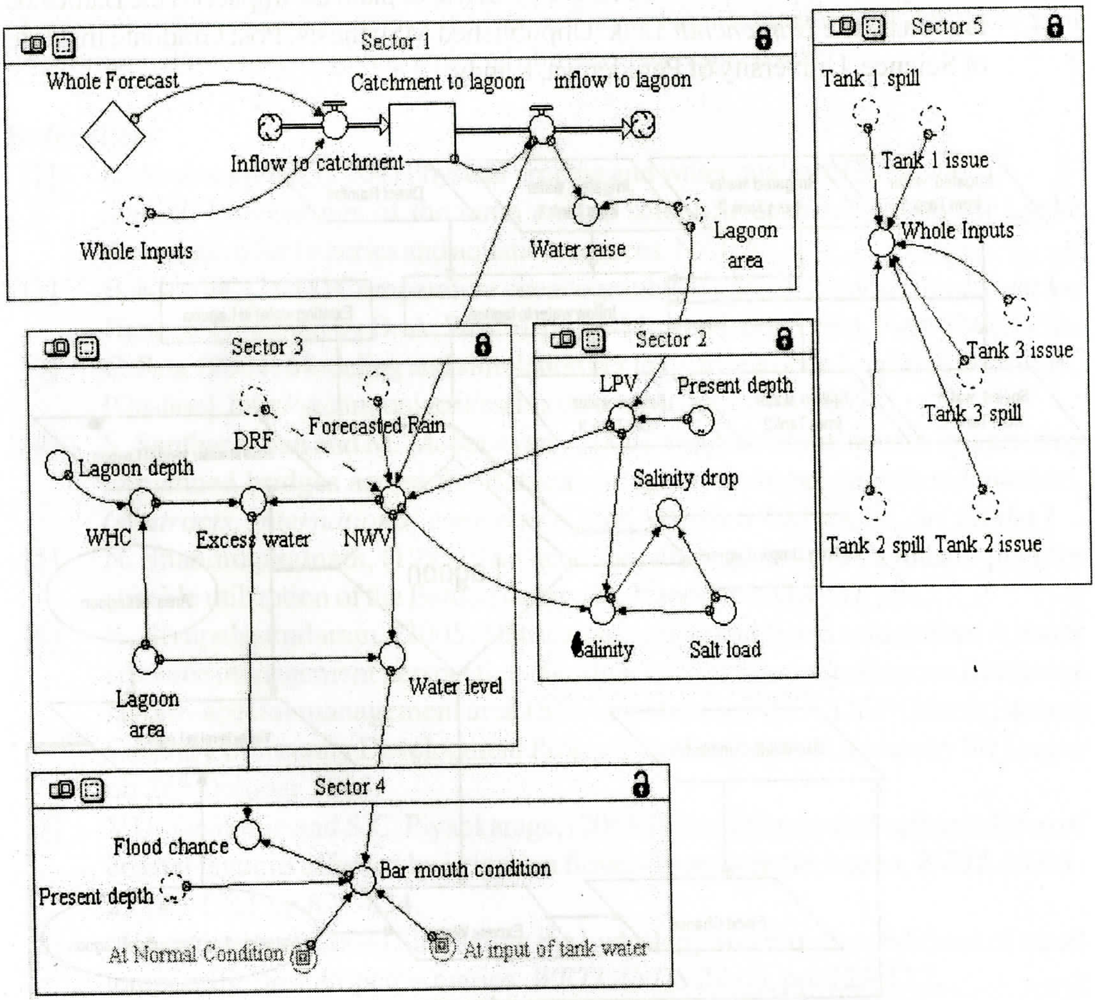

Figure 3: Main simulation model of **TIL** 1.0 (NWV- Net Water Volume; LPV- Existing Volume of water in lagoon; WHC- Water Holding Capacity of lagoon; DRF - Direct Rainfall onto Lagoon)

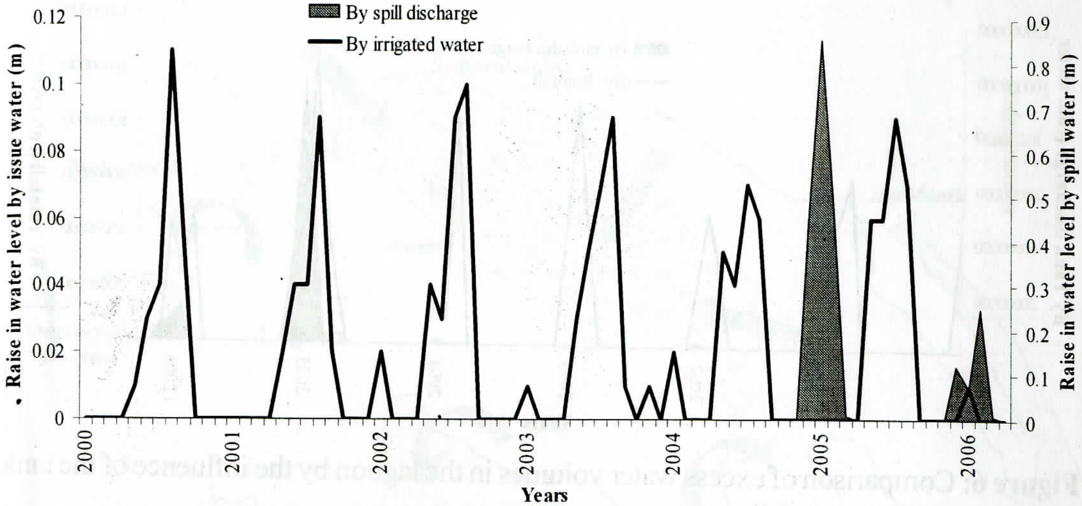

Figure 4: Water raise in Batticaloa Lagoon by the influence *Unnichchai* tank release

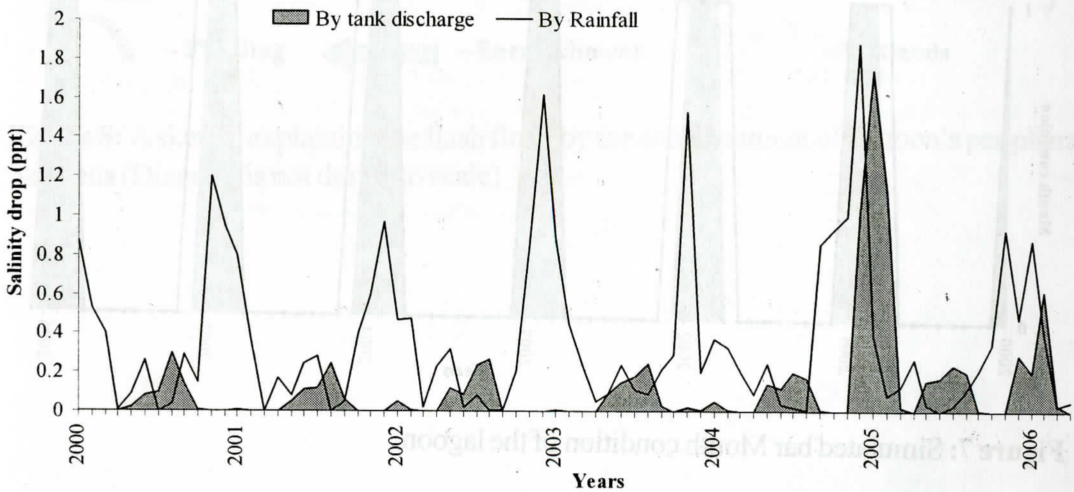

Figure 5: Comparison of temporal variability in Salinity drop by tank discharge and direct rainfall

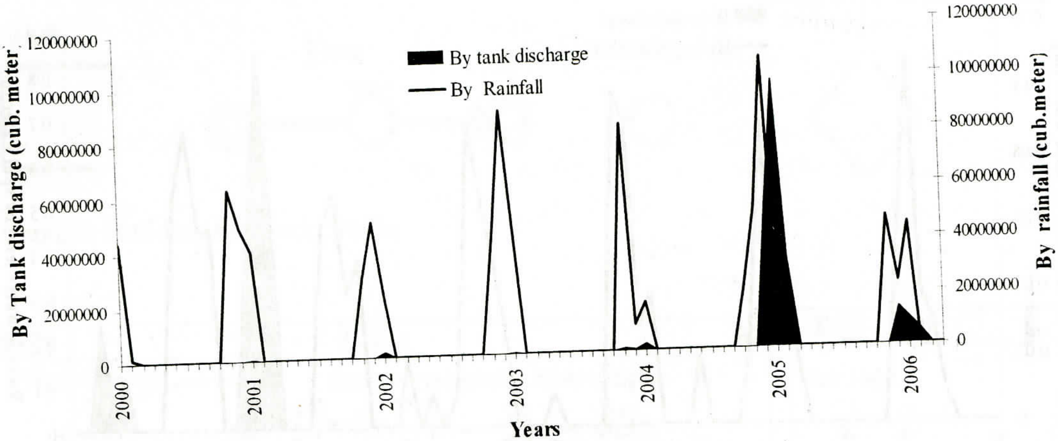

Figure 6: Comparison of excess water volumes in the lagoon by the influence of the tank discharge and direct rainfall

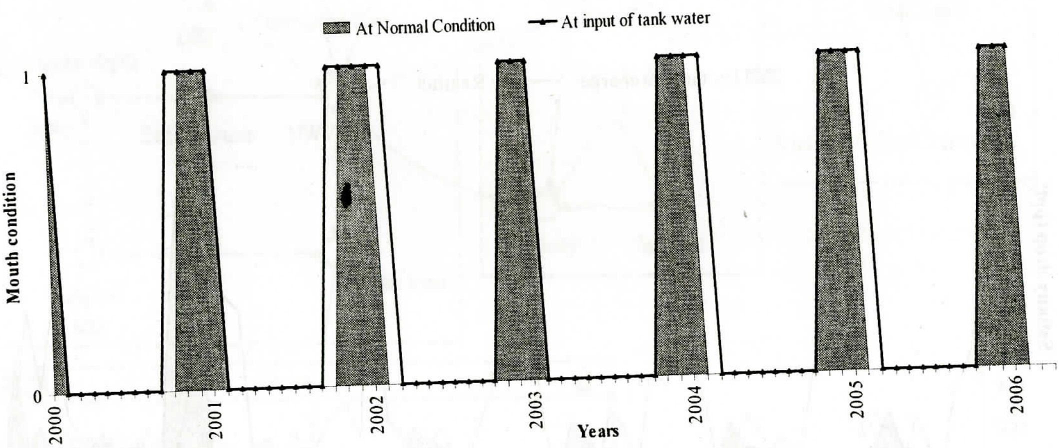

Figure 7: Simulated bar Mouth condition of the lagoon

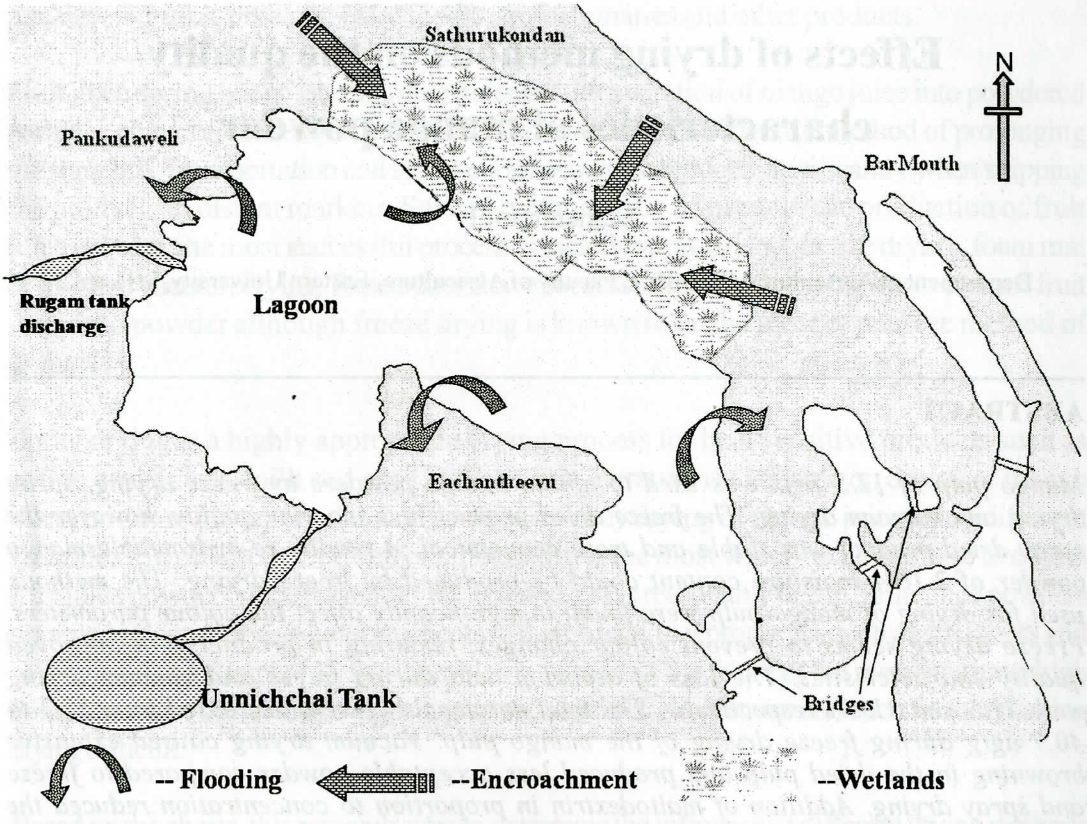

Figure 8: A sketch, explaining the flash flood by the encroachment of Lagoon's peripheral wetlands (Diagram is not drawn to scale)