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Conde Perez dos Santos, Edison; Nunes Cosenza, Carlos Alberto; Amorim, José Carlos Cesar

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# HYBRID SEDIMENT TRANSPORT MODEL FOR THE "LINGUADO" CHANNEL, STATE OF SANTA CATARINA, BRAZIL

*Edison Conde Perez dos Santos*
*COPPE/UFRJ, Federal University of Rio de Janeiro, Brazil*
*E-mail: edison.conde@hotmail.com*

*Carlos Alberto Nunes Cosenza*
*COPPE/UFRJ, Federal University of Rio de Janeiro, Brazil*
*E-mail: cosenzacoppe@gmail.com*

*José Carlos Cesar Amorim*
*Military Institute Engineering (IME), Brazil*
*E-mail: jcamorim@ime.eb.br*

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***ABSTRACT***

This study involves an assessment of various artificial intelligence-related techniques which aim to produce a more robust system for sediment transport modeling. The intelligent systems developed in this research are directly applicable to academic knowledge and use data from a report on "water circulation assessment in the "*Linguado*" Channel and Babitonga Bay - Santa Catarina, Brazil", developed by the Brazilian Military Engineering Institute (*Instituto Militar de Engenharia* - IME). The solution employed for sediment transport was built using an intelligent system from the conception of two hybrid models. The first was a Neuro-Fuzzy (ANFIS) hybrid model for the study of hydrodynamic behavior, aiming to determine flow rate in the channel. The second was a fuzzy genetic model, able to assess sediment transport in the "*Linguado*" Channel. The study's conclusion compares the different effects involved in the dredging equilibrium in the "*Linguado*" Channel according to this hybrid model with the results obtained using a finite element model in the MIKE21® software.

Keywords**:** hydrodynamics, sediment transport, fuzzy logic, genetic algorithm, neural network, ANFIS.

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## 1. INTRODUCTION

Based on questioning the use of natural resources, this paper presents a solution to assess transport sediment in water bodies allowing a consistent assessment of the exploitation of natural resources with minimal environmental impacts. The hybrid model proposed combines a Neuro-Fuzzy (ANFIS) network for flow rate calculation with subsequent use of a Fuzzy Genetic algorithm to calculate sediment transport.

Researchers such as *Feigenbaum*, from the University of Stanford, managed to build a specialized system with 450 rules, using Heuristic Programming. This model, known as HPP, is based on human knowledge and managed to perform patient diagnoses. In addition to this model, other artificial intelligence models based on scientific knowledge-supported rules have also been developed (RUSSEL S., 2008).

The main advantage of mathematical modeling is the capacity to make predictions by simulating future scenarios, such as the presence of yet inbuilt structures or the occurrence of extreme environmental conditions. Hydrodynamic modeling has been seeing wide application in diagnosis with scarce available monitoring data. Hydrodynamic modeling may be also considered as a prerequisite for sediment transport modeling and for water quality modeling (VIEIRA, 2008).

This study proposes a neuro-fuzzy hydrodynamic model to predict the flow rate in the Babitonga Bay, in the Brazilian State of Santa Catarina, combined with a fuzzy genetic model aiming to study sediment transport in the "*Linguado*" Channel. This analysis is necessary due to the sediment input coming from Babitonga Bay through the Channel.

## 2. THEORETICAL FOUNDATION

The estuarine environment undergoes both natural processes and human intervention. Circulating waters suffer the influence from density differences and, mainly, from tidal movements within the estuary, and are also affected by the local morphology. This creates barothropic and baroclinic pressure gradients, which act on the movement and mixing of coastal and river waters (GRACEA *et al*, 2008).

The *Navier Stokes* equation may be used to solve problems involving the specific case of Shallow Waters (SW), as well as in studies about wave movement and water

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circulation ("x" and "y") over a time "t". The equation can be written as follows (BRATT *et al*, 2010).

$$\frac{\partial^2 \eta}{\partial t^2} = \frac{-\partial}{\partial x}\left(C^2 \frac{\partial \eta}{\partial x}\right) - \frac{\partial}{\partial y}\left(C^2 \frac{\partial \eta}{\partial y}\right) + k\frac{\partial \eta}{\partial t} \quad (1)$$

Where “η” is water level height,” $C^2$” is the product of gravitational force and height, and "k" is the friction coefficient of the bottom. Some studies using Artificial Neural Networks (ANNs) have been built based on hydrodynamic models in an attempt to overcome the problem of a non-linear relationship between physical systems and phenomena prediction in marine environments. Vaziri (1997) proposed an ANN model to predict water movement in the Caspian Sea. This model attempted to indicate the monthly level of surface waters.

Deo and Chaudhari (1998) developed a model using ANN techniques, training algorithms whose back propagation error maintained a cascade correlation and adjusted the multivariable function through conjugated gradients thus predicting tides. Tsai & Lee (1999) examined the applicability of a back propagation network (BPN) and neuro-fuzzy (ANFIS) networks in order to predict tide change times.

Regarding sediment transport, published studies provide some models for the transport of pollutants based on equations for SW in an open channel. In such cases, particle trajectories are defined and calculations are performed for the different times of particles' movement in the current, and the model also takes into account distributions according to turbulence regions, providing different speed profiles over a time "t" (HINWOOD, 1979).

$$\frac{\partial c}{\partial t} + \frac{\partial (\mathrm{uc})}{\partial x} - \frac{\partial}{\partial x}\left(\varepsilon_S \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial x}(w - w_S)c - \frac{\partial}{\partial z}\left(\varepsilon_S \frac{\partial c}{\partial z}\right) = 0 \quad (2)$$

In the equation above, "c" is local sediment concentration; "w" is sediment particles' fall velocity, and “$\varepsilon_S$“ is the mixture's sedimentation coefficient. This type of model is applicable to the transport of inert sediments in water. The present paper proposes fuzzy genetic relations for sediment transport, with rules developed for an open channel. An objective function has been coded, forming the binary input vectors.

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## 3. ENVIRONMENTAL DATA

The information used to solve the proposed model were obtained in the study conducted by Military Engineering Institute (IME), and also through existing specific studies of turbidity in the literature, which provide measurements of this variable for eight points considered relevant for this study, points M1 to M8, located throughout the Babitonga Bay, as shown in Figure 1.

Data from the sample used in this study were obtained within 20-minute intervals and stored in the equipment itself. Data collection instruments were placed in the various sampling points mentioned above. The main tidal harmonic constants were estimated using Franco (1988)'s method.

Tidal form factor F was calculated using FEMAR (2000)'s definition, which allowed the development of a tide classification. Tide levels shown for tide stations M1 and M2 are arbitrary, while stations M3, M4, M5, M6, M7 and M8 were leveled in relation to zero, which is represented by the historic average of the spring ebb tides (IBGE's zero level), and to the estimation of river contributions. Salinity and water temperature within the area of interest of this study showed a similar behavior to general water level variations, indicating a possible direct relation of these parameters as functions of tide (SCHETTINI, 1999).

Table 1: Measurement stations used for the sediment transport model

| Station | Location | Latitude | Longitude |
|---|---|---|---|
| Tide station 1-M1 | Monobóia | $26^0$ 13,80’ | $048^0$ 25,05’ |
| Tide station 2-M2 | Penha | $26^0$ 46,50’ | $048^0$ 38,50’ |
| Tide station 3-M3 | Capri Beach | $26^0$ 10,90’ | $048^0$ 34,00’ |
| Tide station 4-M4 | Palmital River (upstream) | $26^0$ 08,00’ | $048^0$ 48,50’ |
| Tide station 5-M5 | Joinville Yatch Club | $26^0$ 17,50’ | $048^0$ 46,00’ |
| Tide station 6-M6 | “Linguado” Channel (North) | $26^0$ 22,00’ | $048^0$ 40,50’ |
| Tide station 7-M7 | Remédios Island | $26^0$ 27,40’ | $048^0$ 34,85’ |
| Tide station 8-M8 | “Linguado” Channel (South) | $26^0$ 22,00’ | $048^0$ 39,00’ |

Source: IME, 2003.

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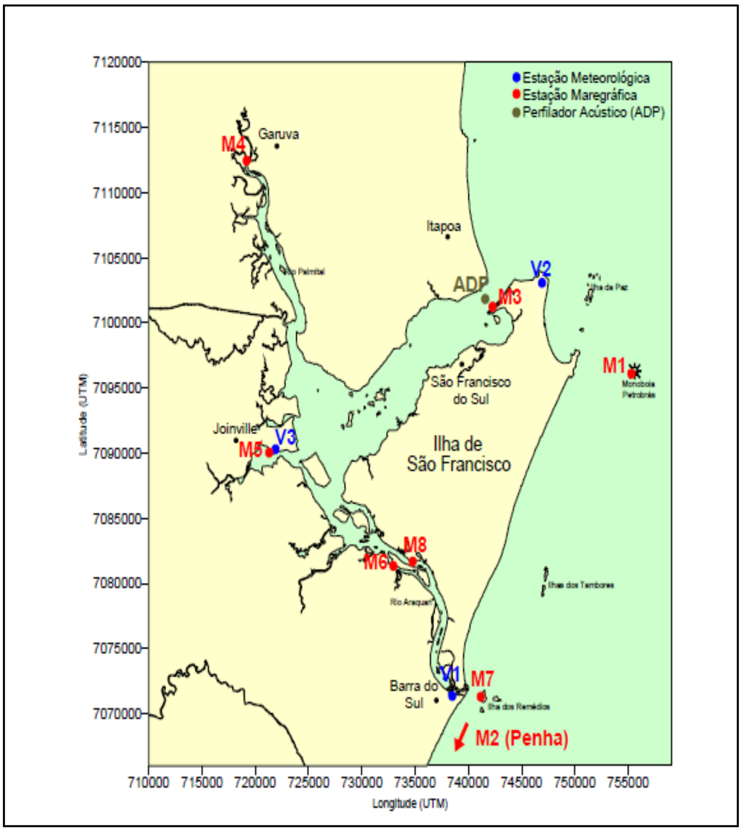


Figure 1: Tide measurement stations used for the sediment transport model
Source: IME, 2003.

## 4. THE HYBRID MODEL

Development of the model's architecture considered four input variables and the operations performed on the inputs of each layer in the ANFIS network. Network structure was formulated according to previously defined rules, considering that the nodes in the first layer, relative to the process of calculating input membership, relate each input of a fuzzy set with its weight (JANG, 1993).

LAYER 1: composed by Inputs, represented by the values observed for the variables bathymetry, tide, winds and roughness, respectively $x_i$, $x_j$, $x_k$, $x_l$ in the membership function TSK, and Output ($O_1$), representing the Value of the (gaussian) membership function whose equation is shown below. The set {wi} represents ANFIS' linear parameters. Model variables are thus fuzzified within the respected values attributed to them, as seen below.

LAYER 2: the input is represented by $O_1$, and the Output by $O_2$, the result of the fuzzy operation to be performed, which consists in multiplying the membership

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degrees whose corresponding linguistic labels (fuzzy sets) are to be combined. This layer's output represents the degree of activation of the developed rule.

LAYER 3: contains the Input set $O_2$ and Output set $O_3$. This stage comprises calculation of the normalized degree of activation by applying the model.

LAYER 4: has Input set $O_3$ and Output set $O_4$. In this layer, the output of layer "3" is multiplied by the function $f_i$. This function is the result of a linear combination of the values of layer 1 inputs *x* with the *y* input values of layer X, as seen below:

$$O_4 = w\,f = v_1 = w_i.\,X_i + w_j\,.X_j + w_k.\,X_k + w_l\,.X_l + b \quad (3)$$

LAYER 5: Input $O_4$; Output $O_5$. This layer comprises calculation of the system's general output, which consists in the sum of the qualified node outputs from layer 4. The nodes from the second layer, represented as "Π" product operators, relate the antecedent connective *e* (where *'e'* represents an operator). Node "N" represents the learning normalization process and the summation node"∑" represents the "average" operator. The inference function (FIS) for ANFIS networks has an activation function ($O_4$) represented by equation 3(JANG, 1993).

The proposed model for sediment transport was built taking into account current fields relative to the various scenarios. To determine the sediment fractions in the riverbed, the domain of the Remobilized Fold Strip includes a single geomorphological region, including the "*Serra do Mar"* Escarpments and Reverse Faults. This region holds the geomorphological units "*Serra do Mar"* and "*São Bento do Sul"* Plateau, which occur at the center and west of the research area, respectively.

The set of all fuzzy genetic rules and their relation with the chromosomes defined the search space. Each chromosome was constituted by "n" parameters, generating a fitness function. For this study, an identification of the rules and their relationship with the respective variables was conducted first, allowing to identify the best dredging for the channel (MENDELL *et* al, 1992; 1995).

In population evolution, individual fitness was assessed first by the result of the crossover operation and then of the mutation operation. Expert knowledge is needed for the evolutionary computation in order to perform the deductive reasoning. That is, an expert's knowledge is important when we wish to deduct or infer a

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conclusion given a set of facts and knowledge. Many formulations applicable to this study with respect to formal knowledge are presented in the literature (ROSS, 1980).

## 5. RESULTS AND DISCUSSION

Learning in the ANFIS consisted in adjusting its parameters, in two steps. The first one included the estimation of parameters, which were assumed to be linear for this model. The second step involved a process of parameter optimization through the application of rules defined for the model according to a backpropagation method. During the optimization step, the algorithm was made with the method of Conjugate Gradient (CG), a method created to solve iterative linear problems. The solution obtained with this method started from the hypothesis that symmetric coefficient matrices are positivelydefined, and the method then progresses and converges in a finite number of iterations.

The definition of initial conditions considered the series of input data obtained and tabulated to calculate flow rate, with a critical value corresponding to the desired degree of confidence, of 0.8; standard deviation of the flow rate variable of 0.5; and margin of error of 0.1. This allowed the definition of sample size as 16 (sixteen) observations, for triangular fuzzy numbers (TRIOLA, F, 1999).

Training of the neuro-fuzzy network in this study consisted in an exercise of numerical optimization of a nonlinear function. The technical literature describes a number of methods of nonlinear optimization (e.g. Bertsekas, 1995). In the present case, the option was to obtain a solution with the aid of the "Solver®" software, which solves this type of problem with a specific process. The use of the "Solver®" software was considered convenient since it is available on MS Excel®, where a numerical optimization add-in can be used to expand Excel's capabilities, allowing the solution to be obtained in a quick, easy and precise way (CHOONG, 2009).

The ANFIS model considered a sample with a moderate number of weights. The data were treated in an ANFIS in the "Solver"® software (Figure 2). Technical literature suggests the method of Conjugated Gradients (CG) to estimate the parameters. However, if parameters are interpreted with the local data, parameter estimation is considered an important aspect for the RMS result, and it may be convenient to use another method in which deviations can be minimized around the

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line (or in this case, around the estimated hyperplane) without biases (CHOONG, 2009).

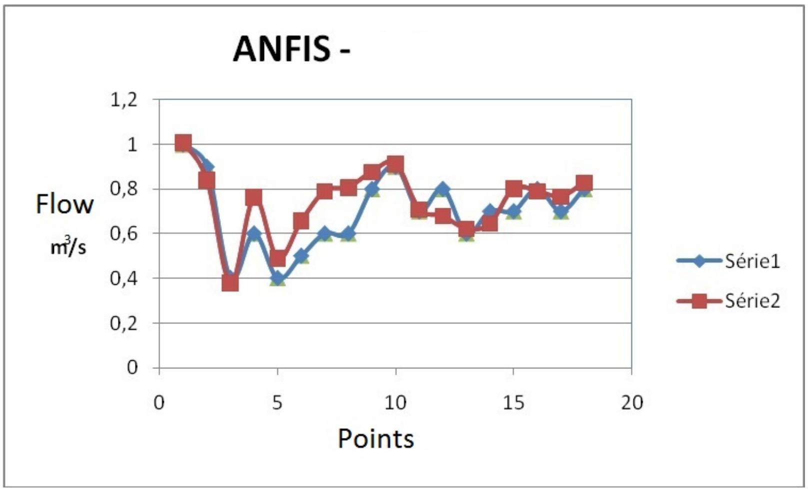


Figure 2: Learning result of the neuro-fuzzy network using the Solver® software in MS Excel®

After 18 (eighteen) observations, "series 2", representing responses provided by the learning of the trained ANFIS, had good superposition with "series 1" (experimental data), indicating good learning by the neuro-fuzzy network. The model indicated the flow rate activation function as being given by the following expression:

$$Y_1 = 0{,}2 - 0{,}1 \cdot X_1 + 0{,}8 \cdot X_2 + 0{,}1 \cdot X_3 + 0{,}2 \cdot X_4 \quad (4)$$

Where $Y_1$ is the flow rate in m³/s, $X_1$ is the channel bathymetry, $X_2$ is the tide in the channel, $X_3$is the winds along the channel and $X_4$ is the roughness along the channel.

The computer software used for simulating sediment transport is the same one used for the hydrodynamic modeling, which will be presented below just for a comparative analysis of results. Programming of the sediment transport model used the results obtained from the hydrodynamic model (ANFIS). The model's evolution was made from water levels collected previously and other hydrodynamic data. The main parameters used in the mathematical modeling were: modeling area: 32.5 km x 45.0 km; channel "Flow rate" forcing; and "channel "Area" forcing.

This study considered a fixed crossover rate, $P_C$ ($Y_i$ (x)), equal to 60%, and a value for mutation rate $P_M$ ($Y_j$ (x)) equal to 1% mutation, as suggested by RODRIGUES F.L. *et al* (2004). Thus, the adjusted fitness function for sediment

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transport is as follows:

$$Y_2 = 0,9 \cdot X_1 + 0,1 \cdot X_2 - 1,85 \quad (5)$$

where $Y_2$ is the sediment concentration in the channel, $X_1$ = flow rate along the channel and $X_2$ is the channel's Area. Training of the GAF model had a RMS of 85% and a good result for the model's statistical fit. Only the variable "Area" had low significance level. This result, however, can be considered acceptable due to the estimator's consistency analysis.

## 6. COMPARISON OF THE RESULTS OBTAINED WITH THE HYBRID MODEL TO THOSE OBTAINED WITH THE FINITE ELEMENT MODEL(MIKE 21®)

Hydrodynamics and sediment transport studies may be performed through simulations involving software using the technique of finite elements, such as MIKE 21®. This section involves the comparison of two sediment transport models. The first one is the finite element-based model MIKE21®, provided by DHI - Danish Hydraulic Institute and the second one is the model built in this study.

In order to study the response of the proposed channel, initially, from the hydrodynamic simulation developed using the hydrodynamic model (ANFIS), 3 (three) scenarios were proposed simulating the width and depth of the channel, as described below:

- Scenario A - Opening of the North Channel, keeping the South Channel closed;
- Scenario B - Opening of the South Channel, keeping the North Channel closed; and
- Scenario C - Opening of the North and South Channels

Table 2: Scenarios studied for dredging of the "*Linguado*" channel / SC- Brazil

| Scenarios | Landfill removal ($m^2$) | | Landfill removal ($m^2$) | | Landfill removal ($m^2$) | |
|---|---|---|---|---|---|---|
| | North | South | North | South | North | South |
| A | X (100,150,200,250) | - | - | - | - | - |
| B | - | - | - | X (100,150,200,250) | - | - |
| C | - | - | - | - | X (100,150,200,250) | X (100,150,200,250) |

Source: IME, 2003.

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These scenarios involved hypothetical situations with different conditions for the variables considered. Therefore, setting up the scenarios considered boundary conditions that conducted to the definition of the variation fields for the variables considered as being the same, with the goal of making these estimates consistent for the purpose of assessing results for the whole set.

The process of solving of the proposed model includes the definition of scenarios believed to have more consistent results, which is an important aspect for decision making processes. The results are summarized in the figures below and show that the results obtained by the hybrid model have good superposition with those of the model of MIKE21® software. Each figure represents a scenario, where "series 2", in red, are the results obtained through the finite element simulation (IME, 2003), while "series 1", in blue, shows the results for the fuzzy-genetic model.

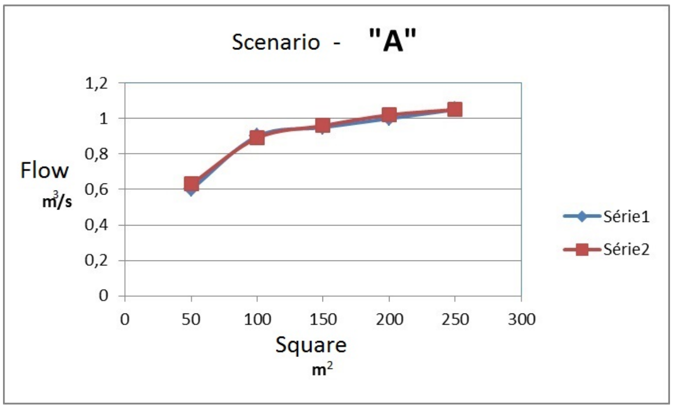


Figure 3: Evolution of experiments for scenario "A"

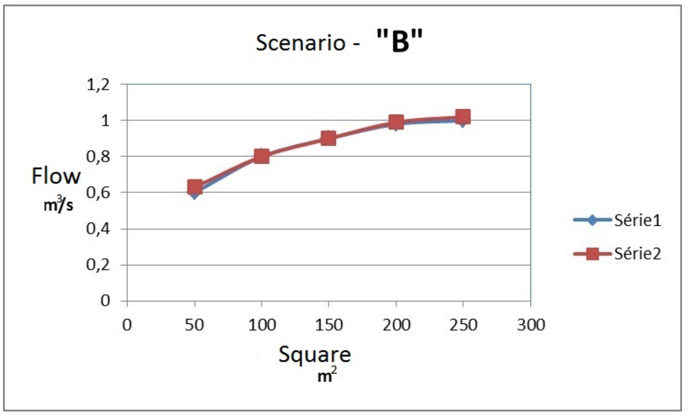


Figure 4: Evolution of experiments for scenario "B"

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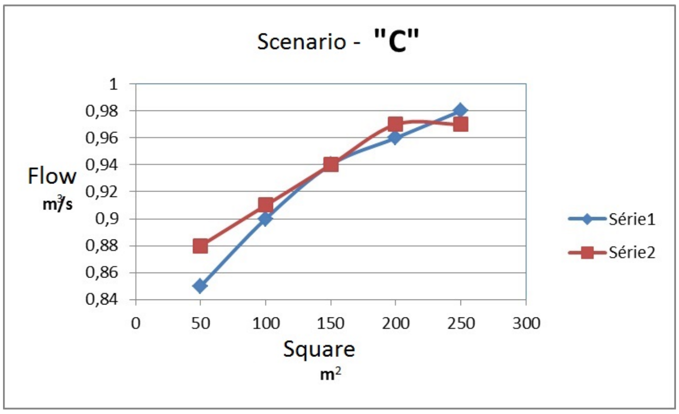


Figure 5: Evolution of experiments for scenario "C"

The results indicate that there is a superposition of the output of both models for scenarios "A" and "B", which is expected due to the correlation of 0.98 between both graphics. This does not occur for scenario "C", however, which considers dredging in both sides of the "*Linguado*" channel; in this case, the models have a superposition of 0.75. It may be considered, however, that the behavior of both models does not show relevant distortions, in light of the aspects discussed above regarding the data, allowing the conclusion that both models provided a good representation of the phenomenon studied.

Sediment transport values during a flow tide found maximum rates for scenario "A", both for the MIKE21® simulation and for the one using the fuzzy genetic algorithm. Simulations with both methods did not show relevant differences, and the maximum flow rate value for this scenario was 1.01 cm/s. Some difference in values was observed for scenario "C", likely because the historical time series for the "South" channel are less reliable, considering that this channel has been closed for a long time and all data used were theoretical extrapolations.

Sediment transport gradients reduce simultaneously with increases in channel depth. This indicates that the system with deeper channels is closer to equilibrium than the system with shallower channels. The GAF model also allows concluding about transported material. According to the Hybrid model, a flow rate of 1.01 cm/s in scenario "A" corresponds to an NTU of 10, that is, a high level of sediment and organic matter transport.

## 7. CONCLUSIONS

This study involved a review of theories for modeling hydrodynamic and sedimentological processes and a review of fuzzy logic and other hybrid systems.

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The analysis of the various possible theoretical modeling perspectives allowed the identification of the most convenient steps to model the process studied here.

Scenarios were defined based on analyzing their relevance for the stability analysis of a tidal channel. The "*Linguado*" Channel in the landfill area is not strictly a tidal channel, although the aspects related to physical mechanisms determining its stability are similar. In this manner, the model used here allows the study of sediment-derived processes, including erosion, sediment transport in water bodies and sediment deposition.

During the search for a better understanding of abstract and concrete aspects involved in the studied scenario and their influences in modeling, a review of the theoretical references relevant to the scenario presented has been conducted, assessing how they could have influenced the decisions in process modeling works, from the closure of the "*Linguado*" Channel in 1935 to the possible implications of this closure, since it may have caused the deposition of a large amount of sediments in the area surrounding the landfill and especially in its northern side, where considerable silting has been happening. This closure may also have caused a general reduction in channel depths in comparison to the period before its closure.

The hybrid models used (neuro fuzzy and fuzzy genetic) were able to learn and reproduce the studied phenomenon; predict the "*Linguado*" Channel's flow rate, which is significantly influenced by the tide in Babitonga Bay; and also identify the strong correlation which exists between the "*Linguado*" Channel's flow rate and the total amount of sediments transported by the Channel.

This study established that the sediment input coming from Babitonga Bay is considerable, being the largest contributor to sediments in the "*"Linguado"*" Channel region in "*Santa Catarina*". Additionally, it established that, despite the considerable sediment input coming from "*Babitonga*" Bay, depth variations in the "*Linguado*" Channel occurred differently from elsewhere in the region.

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