Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

A Primer Discussion for the Application of Automatic Control to Assist Coastal Land-Water Management in the Mekong Delta

Tho H. Nguyen

Department of Electrical Engineering, University of Washington, Seattle, Washington USA
Email: ntho@u.washington.edu

***Key Words**: VRSAP model, St. Venant linearization, adaptive feedback, hydrological system control, coastal management policy*

ABSTRACT

Effective coastal land management is important to the livelihood of its local inhabitant. This challenge is especially important in developing nations. In this paper, we report our effort toward using automatic control to aid the coastal land-water management issues in the Mekong Delta of Vietnam. The report focuses on augmenting the governing dynamics of the existing VRSAP simulation of the MK Delta hydrology such that it would be manageable by a feedback control loop. Steady state linearization and analysis of the governing equations is performed in the general term of the parameters. This technique makes obvious the relationship of each parameter to the formulation of the control problem allowing the engineer to wisely choose an effective parameter for model calibration. An adaptive scheme is then developed to calibrate the chosen control parameter of lateral inflow. Initial experiments from a artificially generated data shows promising results.

1. INTRODUCTION

The challenge - The annual climate of Vietnam is largely divided into two seasons – the rainy season and the dry season. The rainy season lasts between 5 to 6 months (May – October). During the rainy season, the Delta is inundated with fresh water coming down the river permitting advantageous conditions for agricultural production. During the dry season, saline water comes in with the daily tide feeding a thriving aquaculture industry [1], [2]. In order to maximize production, in the early 1990's, the Vietnamese government started construction on a network of sluice gates throughout the Delta to better control its hydrology. The main goals were to extend the fresh water period in agricultural areas and to send saline water to areas that focuses on aquaculture. Since the implementation of the sluice gates, changes in land use and the improvements in the economy have been well documented [1]. However, negative aspects of the gate implementation gradually became apparent. For example, the Delta must be flushed regularly of its acid build-up (acid sulfuric soil) and effluent from the farms. The gates also hinder goods transportation by river, fish migration, etc. [3]. An obvious solution would be to remove the gates to return to the original natural system, however, this isn't an economically or politically feasible solution. In response, scientists are looking for a better way to monitor and schedule the sluice gate operations such that the issues mentioned above can be optimally managed.

Figure 1 (a) – Sluice gate on a Mekong River estuary.

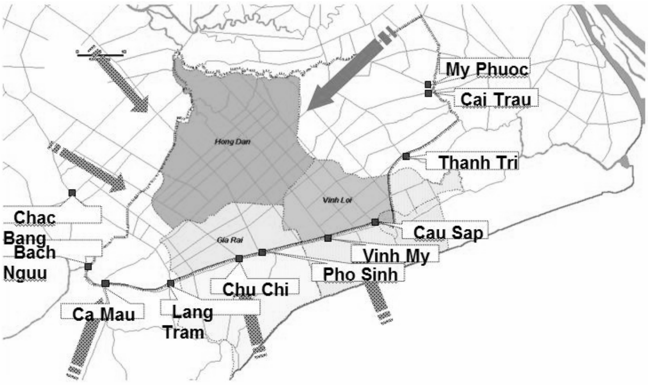

Figure 1 (b) – The Camau protected area. Fresh water shown by blow arrow from the upper Mekong, salt water shown in purple arrow come in with daily tide.

Figure 1(c) - A policy conundrum, reconciling land-use conflict between agriculture in the upper river and aquaculture in the by the coast.

978-1-1234-7890-2/08/$20.00 © 2008 IFAC

10.3182/20080706-5-KR-1001.4027

Addressing the unique properties of a delta environment is the main inspiration for this paper. Specifically, the following properties are taken into consideration:

- Flow is gradual, bi-directional, and complex due to tidal activities, low-gradient (characteristic of a delta), and artificial routing for faming purposes.
- Actuators have digital properties – i.e. the gates can only be completely opened or completely closed.
- Control objectives are inclusive of dynamics beyond engineering.

Problem formulation – The problem being considered can be formulated as: Given a network of open-channel flow whose boundary nodes are either connected to a fresh water river source or saline water from tidal activities – all connections to saline water are regulated by sluice gates, and given that disturbances at boundary nodes can be measured with reasonable accuracy; the goal is to control water distribution at targeted nodes inside the network by manipulating the surrounding sluice gates.

Proposed approach – Automatic control is a strong research area that involves many powerful techniques to manipulate a system for desired performance. Often this area is associated with applications in mechanical and electronic systems. By framing a hydrological system in a control canonical form, most control techniques are applicable. In this paper, the author presents the application of automatic control techniques to the Vietnam River Systems and Plains (VRSAP) model to assist with hydrological and land-use management in selected areas in the Mekong Delta. Specifically, two feedback control loops are applied to the VRSAP model. The inner loop updates hydrological data at real time and output a schedule for the sluice gates that would provide the best match for a desired input. The outer loop provides a method to auto-calibrate the model parameters. A network of specially-adapted remote sensors developed by the author's associated laboratory will be deployed throughout the selected area to provide real-time data [12]. This paper also discusses how these results can assist policy makers, managers, and stock holders in the Mekong Delta to better understand, predict, and manage land-use and hydrological distribution of the Delta.

The paper is formulated as follows: *Section 1* introduces and formulates the problem, *Section 2* discusses the current VRSAP model's technicalities, *Section 3* shows the linearization of the VRSAP's governing equations around steady-state, *Section 4* proposes an adaptive control technique that considers dynamic lateral inflow, *Section 5* presents some initial results and discusses how the solution can assist coastal land management, and *Section 6* concludes the paper.

2. THE VRSAP MODEL

The VRSAP model [4], [8] is popular for modeling the hydrology of the Mekong Delta, Vietnam. This is due to its highly complex internal dynamics that have been refined over several decades to reflect a unique and very complicated system. **Figure 2** shows multiple complexities of the governing dynamics considered in calculations. The model uses the popular St. Venant system of equations for open channel flow. The St. Venant system of equations exists in many similar forms per application needs.

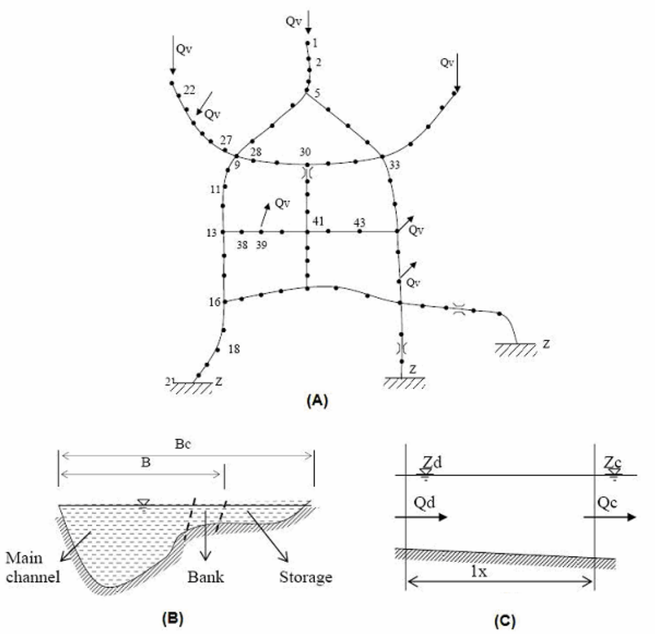

Figure 2 – A graphical representation of the complex St. Venant scheme. (**A**) VRSAP schematization scheme, (**B**) Channel component classification, (**C**) Side view of sectional flow. *Source: VRSAP User Guide.*

Equations (1),(2) below has been revised from a similarly formed system of equations used by the VRSAP model [8] to include dynamic input parameter (*'R')*.

$$\frac{\partial Q}{\partial x} + B\frac{\partial Z}{\partial t} = R \qquad (1)$$

$$\frac{\partial Z}{\partial x} + \frac{\alpha_0}{g}\frac{\partial (Q/w)}{\partial t} + \frac{\alpha}{g}\frac{Q}{w}\frac{\partial (Q/w)}{\partial x} = K \qquad (2)$$

Where:

Q = water flow (m^3/s)
Z = water level (m)
B = canal width at free surface (m)
B_c = canal width averaged over segment (m)
α_0, α = adjustment factor (see [8])
$K = \dfrac{-|Q|/Q}{(wC\sqrt{R})^2}$ is the friction term with Chezy parameter.
$R = f(Q_t)$

$R(Q_t)$ represents dynamic input into a canal (such as lateral inflow). For simplicity, practical conditions imposed on $R(Q_t)$ are added to limit input parameter to effect water flow only, and single-dimensional (with respect to time (t), denoted by the subscript). This formulation is found to be sufficient and especially suitable for a new modeling framework to be reported by the author in subsequent publications.

3. STEADY-STATE LINEARIZATION

The convoluted dynamics of the VRSAP model make it difficult for the application of automatic control. To avoid applying non-linear control methods, engineers often opt to linearize the model then apply linear control techniques [5], [6], [7]. Consider the St. Venant system of equations above, a linearization treatment around steady state is performed – to make the update of empirical boundary conditions as convenient as possible. Since similar analysis has been reported in previous literature, the author invites readers to consult references such as [7],[10]. This paper briefly shows the analysis in the general symbolic form. This extra effort makes obvious the relationship between system parameters and the upstream/downstream transfer function.

From the homogenous form of the system of equations: Replacing $Q = Q_0 + Q'$, and $Z = Z_0 + Z'$ into equations (1), (2) with approximation $w = B_c Z$ and apply the partial derivative:

$$\frac{\partial Q'}{\partial x} + B_c \frac{\partial Z'}{\partial t} = 0 \tag{3}$$

$$\begin{gathered}(1-Fr_0)\frac{\partial Z'}{\partial x} + \frac{\alpha_0}{g w_0}\frac{\partial Q'}{\partial t} + \frac{\alpha}{g}\frac{Q_0}{w_0^2}\frac{\partial Q'}{\partial x} - \\ \frac{\alpha_0}{g}\frac{Q_0 B}{w_0^2}\frac{\partial Z'}{\partial t} = -\left(\frac{\partial K}{\partial Q}Q' + \frac{\partial K}{\partial Z}Z'\right)\end{gathered} \tag{4}$$

Where the partial derivatives with respect to (*Z*) and (*Q*) are evaluated at reference point.

Fr = Froud number, a parameter describing flow condition, defined as $\frac{\alpha B Q^2}{g w^3}$

Taking the Laplace transformation of (3), and (4) by replacing $d/_{dt}(\cdot) = s(\cdot)$ the equations can be rewritten as:

$$\begin{pmatrix} \dfrac{\partial Q'}{\partial x} \\ \dfrac{\partial Z'}{\partial x} \end{pmatrix} = A(s)\begin{pmatrix} Q' \\ Z' \end{pmatrix} \tag{5}$$

The equation is now in the state-space control canonical form and the eigenvalues of (*A*) can be calculated using:

$$\lambda_{1,2} = \frac{1}{2}\left[a_{22} \pm \sqrt{4a_{12}a_{21} + a_{22}^{\;2}}\right] \tag{6}$$

Since (*A*) is scalar in (*x*), the matrix exponential solution to (5) can be calculated as:

$$\begin{pmatrix} Q' \\ Z' \end{pmatrix}_x = P\begin{bmatrix} \exp(\lambda_1 x) & 0 \\ 0 & \exp(\lambda_2 x) \end{bmatrix} P^{-1}\begin{pmatrix} Q' \\ Z' \end{pmatrix}_{x=0}$$

Where $P(\cdot)P^{-1}$ diagonalize *A*.

The result matrix exponential solution is denoted as Φ ,

$$\begin{pmatrix} Q' \\ Z' \end{pmatrix}_x = \Phi\begin{pmatrix} Q' \\ Z' \end{pmatrix}_{x=0} \tag{7}$$

Where $\phi_{11}, \phi_{12}, \phi_{21}, \phi_{22}$ easily calculated and presents no additional challenge.

With the result of (7), we can see that elements of Φ yield the direct transfer functions between upstream (subscript '$_x$') and downstream (subscript '$_0$') water level and flow.

Remark: Different engineers manipulate the structure of Φ in (7) to better reflect their choice of input/output parameters (for example, Baume et al. reports the effect of upstream water release on downstream discharge and the influence of downstream water level on upstream water level).

We analyze the transfer function,

$$\phi_{11} = \frac{\lambda_1 \exp(\lambda_2 x) - \lambda_2 \exp(\lambda_1 x)}{(\lambda_1 - \lambda_2)} \tag{8}$$

Which captures the effect of upstream water flow on downstream flow.

Examination of the formulation of $a_{12,21,22}$ shows that the resulting eigenvalues of *A*, formulated by (6), takes the form:

$$\lambda_{1,2} = c_{1,2}s \tag{9}$$

Constants c_1, c_2 are generalized to include imaginary components. ϕ_{11} is then:

$$\phi_{11}(s) = c_3 e^{xc_2 s} - c_4 e^{xc_1 s} \tag{10}$$

Taking the inverse LaPlace transform yields:

$$\phi_{11}(t) = c_3\delta(t + xc_2) - c_4\delta(t + xc_1) \tag{11}$$

From the time delays of the time-domain transfer function, one can observe that flow at a given point is effected by its upstream (negative time delay) flow and downstream (positive time delay) flow – characteristic of a *sub-critical* flow regime. Intuitively, the delay is characterized by the eigenvalues of *A* and augmented by the canal length, *x*.

4. ADAPTIVE CONTROL FOR AUTO-CALIBRATION MODEL PARAMETERS WITH CONSIDERATION FOR POLICY/MANAGEMENT INPUT

Over many years of being used and built upon, he VRSAP model includes many extraneous parameters that make the computation heavy and extensive. Furthermore, the ambiguous relationship between these parameters and the model's behavior make any calibration difficult.

To implement the result of the previous section, the author proposes the feedback control loop shown in **Figure 3**.

Often used to for highly dynamic systems that operate in dissimilar ranges, an adaptive controller calibrates its parameters or the model's parameters accordingly to achieve the desired output. This method is suitable if the new objective for the system is treated as the system moving into a new range.

In this diagram, an additional scenario select block to reconcile management/policy objectives with previous year's data and current system output to come up with a suitable operating range for the controller. The adaptive controller is shown with standard implementation otherwise.

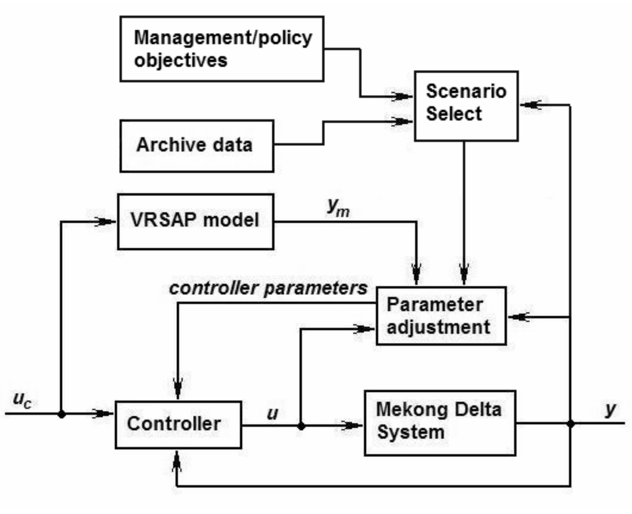

Figure 3 – Adaptive feedback control diagram.

Recall that in the formation shown by (1),(2), lateral input into the canal is allowed to have dynamic property. The challenge is then to prove that with the dynamic additional dynamic input term, adaptive feedback controller can still be formulated. To prove that the additional term poses no new challenge, the author simply shows a simple formulation of an adaptive rule for the controller.

Let us revisit the earlier formulation of (5), where *A(s)* includes the lateral inflow parameter *R = f(Q$_l$)*

Let $\xi = R$ denote the lateral inflow parameter available for adjustment.

Let $J(\xi)$ be a cost function defined as

$$J(\xi) = \frac{1}{2}e^2 \qquad (12)$$

Where $e = y - y_m$ is the error difference between the actual system output and the reference model output (See **Figure** 3).

In minimizing $J(\xi)$, the well-known MIT negative gradient rule can be used:

$$\frac{d\xi}{dt} = -\gamma\frac{dJ}{d\xi} = -\gamma e\frac{de}{d\xi} \qquad (13)$$

Where $\frac{de}{d\xi}$ is also known as the *sensitivity derivative.*

Let us now derive an adaptation law for lateral inflow of the VRSAP model.

A priori knowledge indicates that the primary control actuator for the system is the opening and closing of sluice gates on the rivers. Since the gates have digital properties, as the gates are opened, at steady state the system operates normally. The effect of the controller at steady state can then be modeled as a constant gain ($k_0 \approx 1$). Hence, the system transfer function and reference model transfer function are (respectively),

$$G_{sys} = k_0 G(s)\ ,$$
$$G_{\mathrm{mod}} = k_m \ where\ k_0 \neq k_m \approx 1$$

Remark: The case of closed the gates significantly changes the system's governing dynamics and is a prime example of the system operating in a new range, requiring a switch to the new adaptive rule by the scenario select block.

The system control input is now:

$$u = u_c \xi G_{controller} = u_c \xi k_s \cong u_c \xi\ . \qquad (14)$$

The transfer function between y_c and u_c is:

$$\frac{y}{u_c} = \xi G_{sys} = \xi\, k_0 G(s) \qquad (15)$$

In setting up the lateral inflow parameter, we can choose to set it up in the form:

$$\xi = \frac{k_{\mathrm{mod}}}{k_0}(\zeta_z) \qquad (16)$$

Where ζ_z is a scalar value of lateral input water inflow (*Q*) at the time of evaluation.

The error and sensitivity terms are, respectively:

$$e = y - y_m = \xi k_0 G(s) u_c - k_m G(s) u_c \quad (17)$$

$$\frac{\partial e}{\partial \xi} = k_0 G(s) u_c = \frac{k_0 y_m}{k_{\mathrm{mod}}} \quad (18)$$

Applying the MIT negative gradient rule above, we arrive at the adaptation law:

$$\frac{d\xi}{dt} = -\gamma \frac{k_0}{k_{\mathrm{mod}}} y_m e \quad (19)$$

This adaptation law is straight forward and intuitively sensible. The parameter ξ should be adapted in proportion with output error (e) and estimated model output (y_m), and scaled by the efficiency of the model vs. actual system (k_0/k_{mod}).
From (16), it is easy to see that adjusting the ξ in this case can be conveniently achieved by tuning k_{mod} constant in the model.

So far, only the case of single adjusting parameter is discussed. For multiple parameters, ξ can be treated as a vector. However, this adds complexity to the outer loop analysis and is left for future investigation.

5. INITIAL RESULTS AND A BRIEF DISCUSSION ON HOW IT CAN BETTER AID IN POLICY AND MANAGEMENT OF COASTAL AREAS

Initial Results – From the analysis discussed above, a simulation is created to verify against benchmark canals. The ASCE defines two benchmark canals for the testing of control algorithm in [11]. Given the nature of the low-gradient river bed slope that exist in a delta environment, a more suitable benchmark is created by the author (**Table 1**).

Benchmark canal	
Length	9 Km
Bottom Slope	0.0001 m/m
Bottom Width	6 m
Manning Coeff.	0.18
Side Slope	1.5 m/m
Initial depth	2.3 m
Initial flow	1.263 m^3/sec

Table 1 – Benchmark canal.

By replacing $s = j\omega$ into (7), the frequency response of individual transfer function can be observed. Figure 4 shows the frequency response of ϕ_{11}. Since ϕ_{11} captures the partial effect of downstream discharge due to upstream discharge, the frequency analysis above shows the gain and phase relationship of these parameters. As expected, gain and phase change proportional to frequency increase.

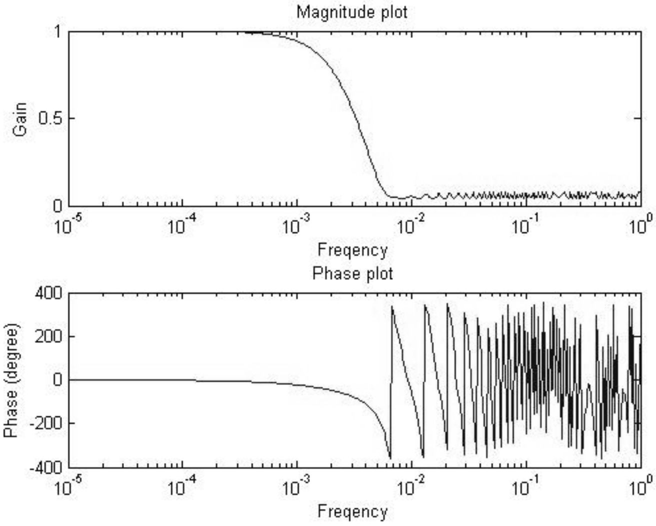

Figure 4 – Calculation of magnitude and phase of

The author further verifies the system behavior against the benchmark data by simulating a canal segment response to a digital actuator (gate) action. As seen in **Figure 5**, the water level response of filling up and being drained as the gate closes upstream and downstream, respectively, behaves as expected.

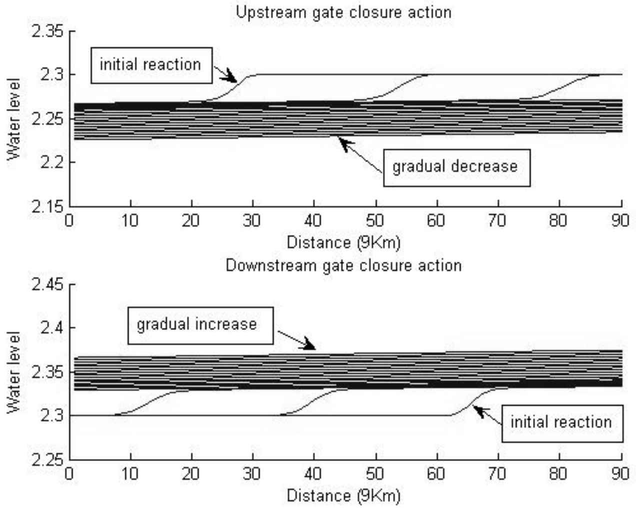

Figure 4 – Simulation reaction of canal water level to upstream (top) and downstream (bottom) gate closure.

Discussion on the Application – The VRSAP is currently being used as a simulation model to aid in land-use management. Using previous year's data, the model is refined to reflect the most current conditions. It is then used to predict the effect of gate operations in different geographical regions. A management policy can be formulated from there. This method has many fundamental shortfalls. Firstly, basing current decisions on a model that was refined using previous year's data is risky. Secondly, without a clear algorithm to adapt the parameters, manual adaptation may exacerbate instead of improve on the model. And thirdly, as management and policy objective changes, being able to adapt on the fly is more desirable.

The results above have demonstrated that we can dynamically integrate current system information into the formulation of the controller. Once an adaptive rule has been formulated, it is followed throughout the system's operation to ensure consistency and benchmark quality results. Furthermore, the proposed scheme is flexible in integrating the high-level management/policy objectives into formulating the controller.

The treatment applied above to the VRSAP can also be implemented on similarly formulated models. An in-depth investigation its properties, such as convergence and efficiency, is left for future work.

6. CONCLUSIONS

The VRSAP model, though popular and proven to work sufficiently for its intended purposes, is not efficient and is currently not suitable for the implementation of automatic control. In this paper, two separate treatments are applied to the system toward demystifying the formulation of the linearized transfer function as reported in past literature. First, a linearization scheme around steady state is taken further to show the relationship between model parameters and the effect on flow regime. Since the flow regime is obtained from observation of the real system, the engineer can go back and wisely choose the appropriate candidate parameter to calibrate in order to accurately reflect it. Secondly, once a parameter is chosen, an adaptive feedback scheme is presented as a method to auto-calibrate the model parameters. An example was shown as proof to develop the adaptation law for the controller inflow parameter. The method presented should be applicable to other similarly formed models. Future development should yield interesting properties and insights.

7. REFERENCES

[1] B. A. George, H. M. Malano, V.K. Tri, N.V. Chien, Hugh Turral (2004). Modelling and Monitoring of Systems Operation: Three Different Irrigation Systems in Vietnam. *Australian Centre for International Agricultural Research (ACIAR) Proceedings No. 118e*: 16-30.

[2] Khue, N.N (1986). Modelling of tidal propagation and salinity intrusion in the Mekong main estuarine system, *Technical paper of Mekong Delta Salinity Instruction Studies, Phase II*. Mekong Secretariat, Bangkok.

[3] H. M. Malano, B. A. George, B. Davidson, V.K. Tri, N.V. Chien (2004). Asset management Modelling for Infrastructure Management in Vietnamese Irrigation Management Companies. *Australian Centre for International Agricultural Research (ACIAR) Proceedings No. 118e*: 51-58.

[4] H. M. Malano, B. A. George, B. Davidson (2004). A Framework for Improving the Management of Irrigation Schemes in Vietnam: an Overview. *Australian Centre for International Agricultural Research (ACIAR) Proceedings No. 118e*: 7-15.

[5] Dooge, J. C. (1987), Napiorkowski, J. J. The effect of the downstream boundary conditions in the linearized st venant equations. *Jl. Mech. Appl. Math.* Vol. 40, Pt. 2.

[6] Dooge, J. C (2004). Bringing it all together. *Hydrology and Earth System Sciences Discussions*. 1: 41-73.

[7] J. P. Baume, J. Sau, P. O. Malaterre (1998). Modeling of irrigation channel dynamics for control purposes. *IEEE Intl. Conf. on Systems, Man, and Cybernetics (SMC) special session*. San Diego, California, USA.

[8] Sub-Institute for Water Resources Planning (2005). VRSAP User Guide. *Obtained by personal correspondence*.

[9] K. J. Astrom, B. Wittenmark (1995). Adaptive Control, Addison, Wesley, Longman.

[10] J. P. Baume, J. Sau (1997). Study of irrigation canal dynamics for control purposes. *Proc. of the intl. workshop on the regulation of irrigation canals (RIC'97)*. Marrakech, Morocco: 3-13.

[11] A.J. Clemmens, T.F. Kacerek, B. Grawitz and W. Schuurmans (1998). "Test cases for canal control algorithms." *Journal of Irrigation and Drainage Engineering* 124(1): 23(8).

[12] T.-T. Pham, D. Burnett, L. Handugan, D. Frashure, J. Chen, L. Bushnell (2007). "Low Cost, Data-Logging Salinity Sensor." *IEEE MTS/OCEANS* . Vancouver, BC.