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Technical Note: Variability of flow discharge in lateral inflow-dominated stream channels

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Variability of flow discharge in lateral inflow-dominated stream channels

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Abstract

The influence of the temporal changes in lateral inflow rate on the discharge variability in stream channels is explored through the analysis of diffusion wave equation (the linearized St. Venant equations). To account for variability and uncertainty, the lateral inflow rate is regarded as a temporal random function. Based on the spectral representation theory, analytical expressions for the covariance function and evolutionary power spectral density of the random discharge perturbation process are derived to quantify variability in stream flow discharge induced by the temporal changes in lateral inflow rate. Upon evaluating the closed-form expressions, it is found that the variability in stream flow discharge increases with distance from the upstream boundary of the channel and time as well. The temporal correlation scale of inflow rate fluctuations plays a positive role in enhancing the variability of the flow discharge in channels. The treatment of the discharge variance gives us a quantitative estimate of uncertainty from the use of the deterministic model.

1 Introduction

Surface runoff originates from precipitation intensities exceeding the infiltration capacity of the surface. This process may result in lateral inflow to stream channels. Significant lateral inflows may contribute to streams during storm-runoff periods when stream reaches are of large lateral watershed area or upslope accumulated area (Jencso et al., 2009). These lateral inflows may be not only a source of water to the streams or channels, but also a source of contaminants to surface water. Agricultural chemicals are frequently mixed into the shallow soil layers and lateral inflows may cause the release and migration of them into streams (Govindaraju, 1996). The effects of the lateral inflows on the stream channels are important in the analysis of contaminant transport in the surface water. Therefore, understanding and quantification of the influence of inflow process on the stream flow discharge is essential for the planning of water resources.

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Natural variability, such as significant variability of rainfall events on both temporal and spatial scales (e.g. Ogden and Julien, 1993; Redano and Lorente, 1993; Wheater et al., 2000; Zhang et al., 2001; De Michele and Bernardara, 2005) and the great heterogeneity of soil types at the ground surface (e.g. Jencso et al., 2009; Fournier et al., 2013) and surface saturation (e.g. Schumann et al., 2009; Riley and Shen, 2014) over a watershed, creates a very complex runoff process on the land surface. Many practical problems of flood wave routing require predictions over relatively large time and space scales. The key question is how one can realistically incorporate the effect of natural heterogeneity into models which extrapolate to predict behavior at large time and space scales. Due to a high degree of the natural heterogeneity of the surface runoff process, the use of deterministic analysis techniques in stream flow modeling is inevitably subject to large uncertainty. The theoretical understanding of variability in flood wave routing is far from complete. Motivated by that, this article focuses on quantification of the discharge variability in lateral-inflow-dominated stream channels.

In the follows, the response of transient stream flow process to spatiotemporal lateral inflow in a diffusion wave model is analyzed stochastically by treating the fluctuations in lateral inflow rate as temporal stationary random processes. The non-stationary spectral techniques are employed to obtain closed-form solutions for quantifying the discharge variability in stream channels. These solutions provide variance relations for flow discharge, and thereby allow for assessing the impact of statistical properties of lateral inflow rate process on the discharge variability.

2 Description of the problem

This study considers the case of unsteady flow in open channels. The equations that describe the propagation of a flood wave with respect to distance along the channel and time in open channels, are the so-called Saint Venant equations, consisting of the continuity equation and the momentum equation. For most flood events, in most rivers the inertial terms from the momentum equation of the Saint-Venant equations are

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negligible as they are small relative to terms arising from gravity and resistance forces (Henderson, 1963; Dooge and Harley, 1967; Daluz Viera, 1983), leading to a simplified model of open channel flow, the diffusion wave equation (e.g. Moussa, 1996; Sivapalan et al., 1997):

$$\frac{\partial Q}{\partial t} + C_\mathrm{d}\left(Q, \frac{\partial Q}{\partial X}\right)\left[\frac{\partial Q}{\partial X} - q_\mathrm{L}\right] = \frac{1}{\sqrt{S_0}}\frac{\partial}{\partial X}\left[D_\mathrm{h}(Q)\left(\frac{\partial Q}{\partial X} - q_\mathrm{L}\right)\right] \tag{1}$$

where Q is the discharge, C_d and D_h are non-linear function of discharge generally known as wave celerity and hydraulic diffusivity, respectively, S_0 is the bed slope, and $q_\mathrm{L}(X, t)$ represents the net lateral inflow distribution. The single diffusion Eq. (1) is formulated by combining the continuity equations for both mass and momentum. The diffusion wave approximation is appropriate for simulations of the flood waves in rivers and on flood plains with milder slopes ranging between 0.001 and 0.0001 (Kazezyılmaz-Alhan, 2012). Most natural flood waves can then be described with the diffusion wave model.

Equation (1) is a nonlinear partial differential equation and has a complex behavior in general. No analytical solution of Eq. (1) is available in the literature. However, the problem can be solved analytically based on some simplifications to the Eq. (1), such as linearization for the case of initial steady uniform flow. Based on expansion of dependent variable and the nonlinear terms in Eq. (1) around the initial condition of steady uniform flow and limitation of the expansion to the first-order variation from the steady state, the result of linearization can be written as

$$\frac{\partial Q'}{\partial t} = D\frac{\partial^2 Q'}{\partial X^2} - C\frac{\partial Q'}{\partial X} + \left[Cq_\mathrm{L} - D\frac{\partial q_\mathrm{L}}{\partial X}\right]. \tag{2}$$

In Eq. (2), $Q' = Q - Q_0 (Q_0 \gg Q', q_\mathrm{L})$, Q_0 is the initial uniform steady-state flow discharge, and C and D represent constant celerity and diffusivity, respectively, which depend on initial uniform flow (velocity and flow depth).The reader may be referred to Dooge and

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Napiorkowski (1987), Ponce (1990), Yen and Tsai (2001) or Tsai and Yen (2001) for the detailed development.

To derive the analytical solution of Eq. (2), one needs to specify the form of $q_L(X, t)$. In the present work, the focus is placed on the case that the net lateral inflow is well-approximated by the following spatial distribution (Lane, 1982; Capsoni et al., 1987; Goodrich et al., 1997; Féral et al., 2003).

$$q_L(X,t) = q_M(t)\exp\left(-\frac{x}{\eta}\right) \tag{3}$$

where q_M is the peak inflow rate and η is the distance along the x-axis for which the inflow rate decreases by a factor e^{-1} with respect to q_M. In particular, q_M is considered to be a temporally correlated stationary random field. It apparent from Eq. (2) that the last two terms associated with the lateral inflow are introduced as the sources of fluctuations in stream flow discharge and treated here as temporally correlated stochastic processes. Equation (2) is then viewed as a stochastic differential equation with a stochastic output Q'. The solution of Eq. (2) will provide a rational basis for quantifying the flow variability through the representation theorem.

Consider that the flow domain is bounded within the range $0 \le x \le L$, the associated initial and boundary conditions can be expressed as

$$Q'(X,0) = 0 \tag{4a}$$

$$Q'(0,t) = 0 \tag{4b}$$

$$\frac{\partial}{\partial x}Q'(L,t) = 0. \tag{4c}$$

Equation (4a) signifies that there is no perturbation from the reference discharge initially while Eq. (4b) assumes no inflow at the upstream boundary at all times. The downstream boundary condition represented by Eq. (4c) is under the condition of a zero-discharge gradient. Morris (1979) showed that this downstream boundary condition is applicable to a large class of problems.

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3 General solutions via spectral theory

The approach followed is to develop the analytical solution of Eq. (2) in the Fourier frequency domain.

Temporal stationarity of the q_M perturbation process admits a spectral representation of the form (e.g. Priestley, 1965)

$$q_\mathrm{L} = q_\mathrm{M}(t)\exp\left(-\frac{x}{\eta}\right) = \exp\left(-\frac{x}{\eta}\right)\int_{-\infty}^{\infty} e^{i\omega t}\mathrm{d}Z_q(\omega) \tag{5}$$

where ω is the frequency parameter, $Z_q(\omega)$ is an orthogonal process, and $\mathrm{d}Z_q$ is a zero-mean orthogonal increment process with

$$E[\mathrm{d}Z_q(\omega_1)\mathrm{d}Z_q^*(\omega_2)] = S_{qq}(\omega_1)\delta(\omega_1-\omega_2)\mathrm{d}\omega_1\mathrm{d}\omega_2 \tag{6}$$

in which $E[–]$ denotes the ensemble average, the superscript asterisk stands for the complex-conjugation operator, and S_{qq} (–) is the power spectral density for the stationary random q_M perturbation process. On the other hand, without the restriction on the assumption of stationarity the random perturbed quantities Q' may be expressed in the form of the Fourier–Stieltjes integral representation as (e.g. Priestley, 1965; Li and McLaughlin, 1991)

$$Q'(X,t) = \int_{-\infty}^{\infty}\Theta_{Qq}(X,t,\omega)\mathrm{d}Z_q(\omega) \tag{7}$$

where Θ_{Qq} (–) is the transfer function depending on space, time, and frequency.

It follows from Eqs. (5) and (7) that Eq. (2) takes the form

$$\frac{\partial\Theta_{Qq}}{\partial t} = D\frac{\partial^2\Theta_{Qq}}{\partial X^2} - C\frac{\partial\Theta_{Qq}}{\partial X} + \exp\left(-\frac{X}{\eta}+i\omega t\right)\left(C+\frac{D}{\eta}\right) \tag{8}$$

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subject to the following initial and boundary conditions

$$\Theta_{Qq}(X,0) = 0 \tag{9a}$$

$$\Theta_{Qq}(0,t) = 0 \tag{9b}$$

$$\frac{\partial \Theta_{Qq}}{\partial X}(L,t) = 0. \tag{9c}$$

The method of eigenfunction expansion is used to solve this inhomogeneous boundary value problem and the solution of Eq. (8) with Eq. (9) is:

$$\Theta_{Qq}(X,t,\omega) = 2\frac{D}{L}\left(\upsilon + \frac{1}{\mu}\right)\exp\left(\frac{\upsilon}{2}\xi\right)\sum_{n=0}^{\infty}\frac{a_n - \beta\exp(-\beta)\cos(n\pi)}{\beta^2 + a_n^2}\sin(a_n\xi) \times \frac{\exp(-i\omega t) - \exp(-F_n t)}{F_n - i\omega} \tag{10}$$

where $\upsilon = \mathrm{CL}/D$, $\mu = \eta/L$, $a_n = \pi(2n+1)/2$, $\xi = X/L$, $\beta = (\upsilon/2) + 1/\mu$, and $F_n = D[a_n^2 + \upsilon^2/4]/L^2$. Rewriting Eq. (7), using Eq. (10), yields the solution of Eq. (2) in frequency domain as

$$Q'(X,t) = 2\frac{D}{L}\left(\upsilon + \frac{1}{\mu}\right)\exp\left(\frac{\upsilon}{2}\xi\right)\sum_{n=0}^{\infty}\frac{a_n - \beta\exp(-\beta)\cos(n\pi)}{\beta^2 + a_n^2}\sin(a_n\xi) \times \int_{-\infty}^{\infty}\frac{\exp(-i\omega t) - \exp(-F_n t)}{F_n - i\omega}\mathrm{d}Z_q(\omega). \tag{11}$$

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The covariance function of the flow discharge field, C_{QQ} (–), can be computed based on the representation theorem for Q' by

$$C_{QQ}(X,t_1,t_2) = E[Q'(X,t_1)Q'^*(X,t_2)] = \int_{-\infty}^{\infty} \Theta_{Qq}(X,t_1,\omega)\Theta^*_{Qq}(X,t_2,\omega)S_{qq}(\omega)\mathrm{d}\omega$$

$$= 4\frac{D^2}{L^2}\left(\upsilon+\frac{1}{\mu}\right)^2 \exp(\upsilon\xi)\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{\sin(a_m\xi)\sin(a_n\xi)}{\left(\beta^2+a_m^2\right)\left(\beta^2+a_n^2\right)}$$

$$\times\left\{a_m a_n-\beta\exp(-\beta)\left[a_m(-1)^m+a_n(-1)^n\right]+\beta^2(-1)^{m+n}\exp(-2\beta)\right\}$$

$$\times\int_{-\infty}^{\infty}\frac{\begin{array}{c}\exp[i\omega(t_1-t_2)]-\exp(-F_m t_1-i\omega t_2)\\ -\exp(i\omega t_1-F_n t_2)+\exp(F_m t_1+F_n t_2)\end{array}}{\left(F_mF_n+\omega^2\right)+i\frac{D}{L^2}\left(a_n^2-a_m^2\right)\omega}S_{qq}(\omega)\mathrm{d}\omega \qquad (12)$$

where $a_m = \pi(2m+1)/2$ and $F_m = D[a_m^2+\upsilon^2/4]/L^2$. The variance of flow discharge fluctuations is obtained by evaluating Eq. (12) at zero time lag as

$$\sigma_Q^2(X,t) = C_{QQ}(X,t,t) = 4\frac{D^2}{L^2}\left(\upsilon+\frac{1}{\mu}\right)^2\exp(\upsilon\xi)\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{\sin(a_m\xi)\sin(a_n\xi)}{\left(\beta^2+a_m^2\right)\left(\beta^2+a_n^2\right)}$$

$$\times\left\{a_m a_n-\beta\exp(-\beta)\left[a_m(-1)^m+a_n(-1)^n\right]+\beta^2(-1)^{m+n}\exp(-2\beta)\right\}$$

$$\times\int_{-\infty}^{\infty}\frac{1-\exp[-(F_m+i\omega)t]-\exp[(i\omega-F_n)t]+\exp[(F_m+F_n)t]}{\left(F_mF_n+\omega^2\right)+i\frac{D}{L^2}\left(a_n^2-a_m^2\right)\omega}S_{qq}(\omega)\mathrm{d}\omega. \qquad (13)$$

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In addition, following Priestley (1965), the variance of the Q' process may be written in the form of

$$\sigma_Q^2(X,t) = \int_{-\infty}^{\infty} |A_t(X,t,\omega)|^2 E\left[dZ_q(\omega)dZ_q^*(\omega)\right] \tag{14}$$

so that the evolutionary power spectral density of the non-stationary random process can be defined as

$$E\left[dZ_Q(X,t,\omega)dZ_Q^*(X,t,\omega)\right] = |A_t(X,t,\omega)|^2 E\left[dZ_q(\omega)dZ_q^*(\omega)\right] \tag{15}$$

where A_t (–) is referred to as the modulating function of the non-stationary process. The evolutionary spectrum has the same physical interpretation as the spectrum of a stationary process, namely, that it describes the distribution of mean square signal content (or fluctuations) of the random process at a given time t. Comparing Eq. (14) to Eq. (13) leads Eq. (15) to

$$\begin{aligned} S_{QQ}(X,t,\omega) = & 4\frac{D^2}{L^2}\left(\upsilon+\frac{1}{\mu}\right)^2 \exp(\upsilon\xi)\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\frac{\sin(a_m\xi)\sin(a_n\xi)}{\left(\beta^2+a_m^2\right)\left(\beta^2+a_n^2\right)} \\ & \times\left\{a_m a_n - \beta\exp(-\beta)\left[a_m(-1)^m + a_n(-1)^n\right] + \beta^2(-1)^{m+n}\exp(-2\beta)\right\} \\ & \times\frac{1-\exp[-(F_m+i\omega)t] - \exp[(i\omega - F_n)t] + \exp[(F_m+F_n)t]}{\left(F_mF_n+\omega^2\right) + i\frac{D}{L^2}\left(a_n^2-a_m^2\right)\omega} S_{qq}(\omega) \end{aligned} \tag{16}$$

where S_{QQ} (–) is the spectral density of the Q' perturbation process.

The infinite series in Eq. (10) converges rapidly when $\tau_c = Dt/L^2 \gg 1/\pi^2$. Accordingly, Eq. (10) can reduce to

$$\Theta_{Qq}(X,t,\omega) = \frac{D}{L}\left(\upsilon+\frac{1}{\mu}\right)\frac{\pi-2\beta\exp(-\beta)}{\beta^2+\frac{\pi^2}{4}}\exp\left(\frac{\pi}{2}\xi\right)\sin\left(\frac{\pi}{2}\xi\right)\frac{\exp(i\omega t)-\exp(-\tau)}{\rho+i\omega} \tag{17}$$

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where $\rho = D[\pi^2 + \upsilon^2]/(4L^2)$ and $\tau = \rho t$. The timescale of the hydraulic system, τ_c, is referred to as the hydraulic response time (Gelhar, 1993). Here, it is interpreted as the characteristic time for a change in upstream discharge to reach the downstream end of the stream. For most practical applications, it is much greater than one, which is the main interest of this study.

The use of Eq. (17), in turn, simplifies Eqs. (13) and (16), respectively, to

$$\sigma_Q^2(X,t) = \frac{D^2}{L^2}\left(\upsilon + \frac{1}{\mu}\right)^2 \frac{[\pi - 2\beta\exp(-\beta)]^2}{\left(\beta^2 + \frac{\pi^2}{4}\right)^2} \exp(\upsilon\xi)\sin^2\left(\frac{\pi}{2}\xi\right) \times \int_{-\infty}^{\infty} \frac{1 - 2\exp(-\tau)\cos(\omega t) + \exp(-2\tau)}{\omega^2 + \rho^2} S_{qq}(\omega)\mathrm{d}\omega \tag{18}$$

$$S_{QQ}(X,t,\omega) = \frac{D^2}{L^2}\left(\upsilon + \frac{1}{\mu}\right)^2 \frac{[\pi - 2\beta\exp(-\beta)]^2}{\left(\beta^2 + \frac{\pi^2}{4}\right)^2} \exp(\upsilon\xi)\sin^2\left(\frac{\pi}{2}\xi\right) \times \frac{1 - 2\exp(-\tau)\cos(\omega t) + \exp(-2\tau)}{\omega^2 + \rho^2} S_{qq}(\omega). \tag{19}$$

Equation (19) states that the spectrum of the discharge is a result of a competitive relation between the signal frequency and the properties of the stream channel and inflow. Generally, it is very difficult to quantify the variability of inflow rate. Equation (19) thus provides information about the nature of inflow processes. For example, based on an observed discharge perturbation time series with known hydraulic parameters, the nature of inflow processes may be determined from Eq. (19). After normalizing by the spectral density S_{qq} (–), the evolutionary power spectral density Eq. (19) as a function of dimensionless frequency for various time scales and location are graphed in Fig. 1a and b, respectively. It shows that the spatial variation of spectral amplitude associated with a given frequency increases with the time and distance from the upstream bound-

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ary as well. It reveals that the variability of flow discharge increases with time and distance.

4 Closed-form expressionss for the variance and spectral density of discharge fluctuations

In this work, the spectrum of red noise is used to evaluate Eqs. (18) and (19) explicitly. The analysis of discharge variability in this section assumes an exponential form for the autocovariance function of the random fluctuations in the peak inflow rate (Jin and Duffy, 1994; Kumar and Duffy, 2009), namely,

$$C_{qq}(\ell_\mathrm{S}) = \sigma_q^2 \exp\left(-\frac{|\ell_\mathrm{S}|}{\lambda}\right) \tag{20a}$$

which has the following spectral density function

$$S_{qq}(\varpi) = \frac{\sigma_q^2 \lambda}{\pi(1+\lambda^2\varpi^2)} \tag{20b}$$

where ℓ_S is the time lag and σ_q^2 and λ are, respectively, the variance and temporal correlation scale of peak inflow rate fluctuations.

Upon substituting Eq. (20b) into Eq. (18) and integrating it over the frequency domain, one obtains the following expression for the variance of flow discharge fluctuations as

$$\begin{aligned}\sigma_Q^2(X,t) =& 16\sigma_q^2 L^2 \frac{\left(\upsilon+\frac{1}{\mu}\right)^2}{(\pi^2+\upsilon^2)^2} \frac{[\pi-2\beta\exp(-\beta)]^2}{\left(\beta^2+\frac{\pi^2}{4}\right)^2} \exp(\upsilon\xi)\sin^2\left(\frac{\pi}{2}\xi\right) \\ &\times \tau_R \left\{\frac{1+\exp(-2\tau)}{1+\tau_R} - 2\frac{\exp(-\tau)}{1-\tau_R^2}\left[\exp(-\tau) - \tau_R \exp\left(-\frac{\tau}{\tau_R}\right)\right]\right\}\end{aligned} \tag{21}$$

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where $\tau_R = \rho\lambda$. It is apparent from Eq. (21) that there is a linear relationship between the variances of fluctuations in the flow discharge and inflow rate, implying that the flow variability increases linearly with the heterogeneity of the inflow rate. With Eq. (20b), the resulting expression for the evolutionary power spectral density in Eq. (19) is given by

$$S_{QQ}(X,t,\varpi) = \frac{\sigma_q^2}{\pi}\frac{D^2}{L^2}\left(\upsilon + \frac{1}{\mu}\right)^2 \frac{[\pi - 2\beta\exp(-\beta)]^2}{\left(\beta^2 + \frac{\pi^2}{4}\right)^2}\exp(\upsilon\xi)\sin^2\left(\frac{\pi}{2}\xi\right) \times \frac{1 - 2\exp(-\tau)\cos(\varpi t) + \exp(-2\tau)}{\varpi^2 + \rho^2}\frac{\lambda}{1+\lambda^2\varpi^2}. \tag{22}$$

Figure 2 shows the plot of the dimensionless variance of discharge fluctuations in Eq. (21) as a function of dimensionless time for various dimensionless temporal correlation scales of inflow rate fluctuations. The figure indicates that the variability of flow discharge induced by the variation of inflow rate increases gradually with time toward its asymptotic value at large time. The increase of discharge variability with the temporal correlation scale at a fixed time agrees with common physical intuition. A larger correlation scale means a larger temporal consistency of fluctuations in the inflow rate, which leads in turn to larger deviations of flow discharge from the initial uniform steady-state flow discharge.

Variation of flow discharge with the distance from the upstream boundary is depicted in Fig. 3 according to Eq. (21). As noted in the figure, the variability of flow discharge grows monotonically with distance, implying that due to the naturally inherent variability of lateral inflow, uncertainty in the flow discharge calculations from a deterministic model increases with the distance from the upstream boundary. In other words, the prediction of flow discharge distribution based on the deterministic simulation results is subject to the largest uncertainty in the downstream region. It is the downstream region that is important in most real applications of modeling and Eq. (21) provides a way of assessing the variation around the deterministic model prediction.

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In many practical applications involving prediction over a large scale, it requires measurement of uncertainty. SD is the best way to accomplish that. In this sense, the prediction results from a deterministic model are treated as mean values. The mean value plus one SD (square root of Eq. 21) provides a rational basis for extrapolating relatively small-scale field observations to these large space scales. It is about 68.27% of the time that value of flow discharge will lie within the range of the mean discharge ± one SD.

5 Conclusions

The problem of fluctuations in flow discharge in open channels in response to temporal changes in lateral inflow rate is investigated stochastically for a finite flow domain. In this study, the inflow perturbation field is modeled as a temporally stationary random process. For a complete stochastic description of flow discharge variability, expressions for the covariance function and evolutionary power spectral density of the random flow discharge perturbation process are developed. These expressions are obtained using a spectral representation theory. The variance relation developed here provides a rational basis for quantifying the uncertainty in applying the deterministic model.

It is found from our closed-form expressions that the discharge variability in stream channels induced by the temporal changes in lateral inflow rate increases gradually with time toward its asymptotic value at large time. A larger temporal correlation scale of inflow rate fluctuations which is of a more persistence of inflow perturbation process will introduce more variability of the flow discharge. The increase of discharge variability with distance from the upstream boundary suggests that prediction of flow discharge distribution in channels using a deterministic model is subject to large uncertainty at the downstream of the stream channel.

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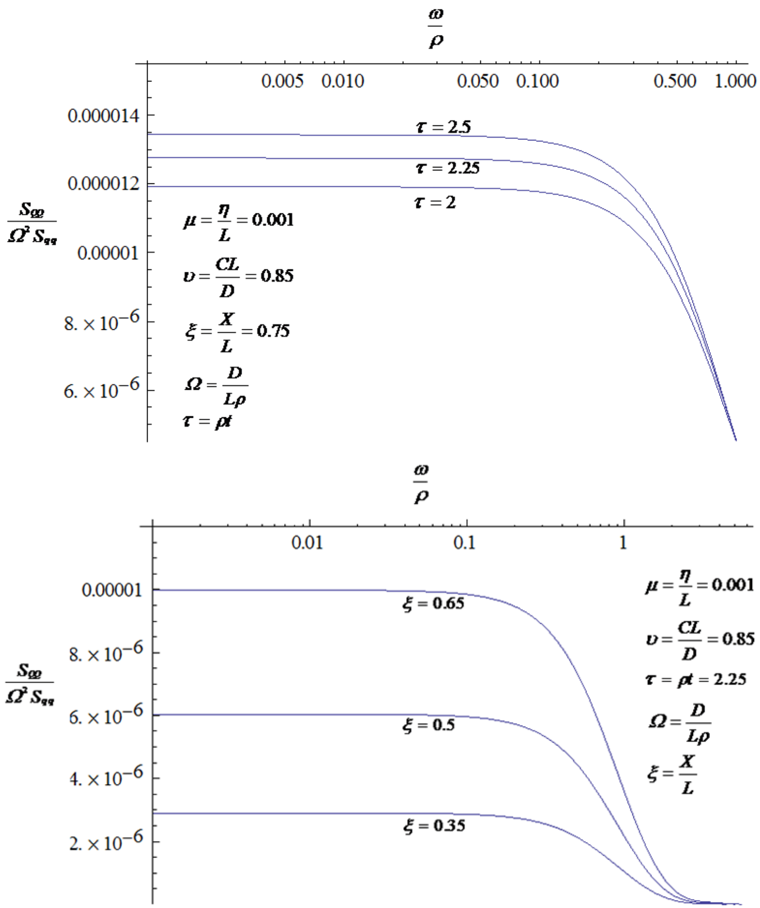

Figure 1. Dimensionless evolutionary power spectral density as a function of dimensionless frequency for various **(a)** time scales and **(b)** location.

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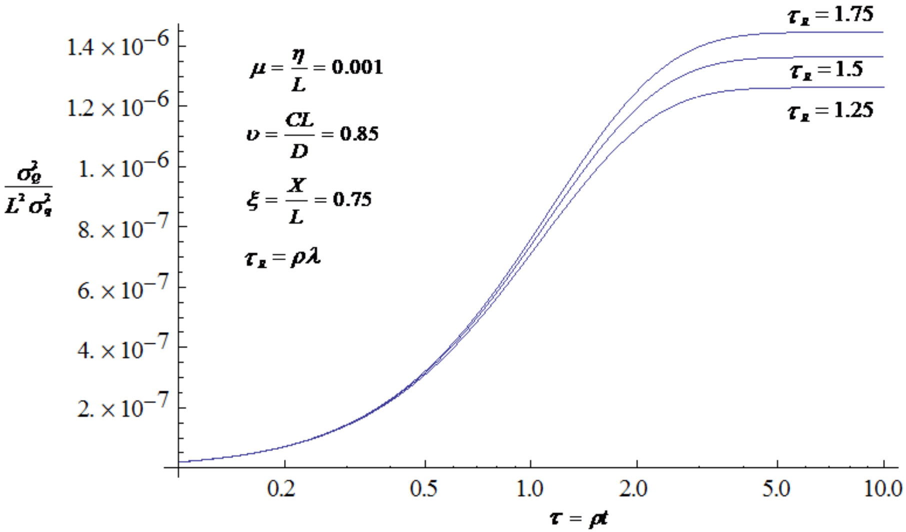

Figure 2. Dimensionless variance of discharge fluctuations as a function of dimensionless time for various dimensionless temporal correlation scales of inflow rate fluctuations.

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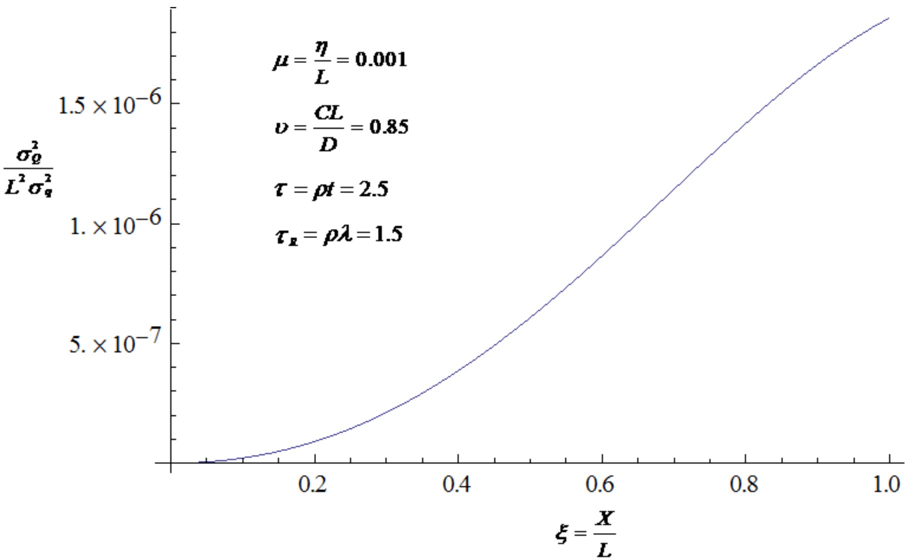

Figure 3. Dimensionless variance of discharge fluctuations as a function of dimensionless distance from the upstream boundary.

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