Stream Reaeration in Nonuniform Flow: Macroroughness Enhancement[a]

Discussion by Hubert Chanson[3] and Luke Toombes[4]

The authors presented two papers that are a welcome addition to the topic of water quality and stream reaeration. The renewal theory and small eddy model provide interesting results for smooth and small-roughness channels. The discussers feel, however, that the second paper highlights some limits of the method, particularly when free-surface aeration takes place.

The present discussion provides additional material on the problem of stream reaeration in the presence of "whitewater" (i.e., air bubble entrainment). It complements the original paper, and some references are added, including large-scale data.

MASS TRANSFER EQUATION AND AIR-WATER INTERFACE AREA

The mass transfer rate of a chemical across an interface varies directly as the coefficient of molecular diffusion and the negative gradient of gas concentration. If the chemical of interest is volatile (e.g., oxygen), the transfer is controlled by the liquid phase, and the gas transfer of the dissolved chemical across an air-water interface is usually rewritten as

$$\frac{\partial}{\partial t} C_{\text{gas}} = k_L \cdot a \cdot (C_{\text{sat}} - C_{\text{gas}}) \tag{13}$$

where k_L = liquid film coefficient; a = specific surface area defined as the air-water interface area per unit volume of air and water; C_{gas} = local dissolved gas concentration; and C_{sat} = concentration of dissolved gas in water at equilibrium [e.g., Gulliver (1990)].

Eq. (13) is more general than the authors' (1) because it accounts for the variations of dissolved gas concentration in the cross section as well as the effects of hydrostatic pressure on the equilibrium concentration. More importantly, (13) includes the effect of air bubble entrainment and the drastic increase in interfacial area. Experimental measurements in supercritical flows down a flat chute recorded local specific interface area of up to 110 m^2/m^3 (m^{-1}) with depth-averaged (bulk) interface area ranging from 10 to 21 m^{-1} (Chanson 1997). Larger specific interface areas were recorded in developing shear flows. Local interface areas of up to 400 m^{-1} were observed in hydraulic jumps and maximum specific interface areas of up to 550 m^{-1} were measured in plunging jet flows (Chanson and Brattberg 1997). These examples illustrate the potential for aeration enhancement in the presence of whitewater as, for example, in Fig. 7.

Chanson (1995) applied (13) to smooth chute spillways. Both open channel flow aeration and hydraulic jump air entrainment were considered. The results were successfully compared with the prototype data of Rindels and Gulliver (1989).

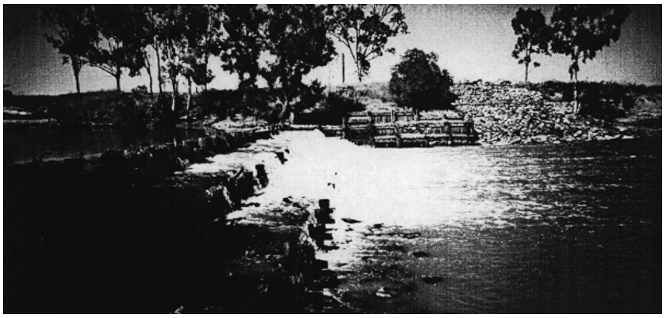

FIG. 7. In-Stream Reaeration at Stepped Cascade: Cunningham Weir, Dumaresq River, Australia, in February 1998 during Low Overflow (View from Right Bank)

Experimental Measurements of Air-Water Interface Area

Measurements of air-water interface area derive from the air-water flow properties including void fraction, velocity, bubble size, and bubble count. In monosize bubbly flows, the air-water interface area may be estimated from the air bubble size:

$$a = 6 \cdot \frac{C}{d_{ab}} \tag{14}$$

where C = concentration of undissolved air (i.e., void fraction); and d_{ab} = bubble diameter. For a nonconstant bubble size distribution, the local specific interface area equals

$$a = \int_0^{+\infty} 6 \cdot \Pr(d_{ab}) \cdot \frac{C}{d_{ab}} \cdot d(d_{ab}) \tag{15}$$

where $\Pr(d_{ab})$ = probability of bubble size d_{ab}.

Experimental measurements with intrusive probes (e.g., resistivity, optical fiber) do not provide bubble diameters but bubble chord length and bubble count data. For any bubble shape, bubble size distribution, and chord length distribution, the mean chord length size (that is, the number mean size) equals $C \cdot V/F_{ab}$ where V = local velocity and F_{ab} = bubble count (that is, the number of bubbles impacting the probe per second). The specific air-water interface area may then be estimated as

$$a = \frac{4 \cdot F_{ab}}{V} \tag{16}$$

Eqs. (14)–(16) are valid in bubbly flows. In high air content regions ($C > 0.3$ to 0.5), the flow structure is more complex and the result is not exactly equal to the true specific interface area. Then a becomes simply proportional to the number of air-water interfaces per unit length of air-water mixture (i.e., $2 \cdot F_{ab}/V$).

CASCADE REAERATION

A related form of aeration enhancement by macroroughness is the reaeration cascade. Stepped cascades are very efficient because of the strong turbulent mixing associated with substantial air entrainment (e.g., Fig. 7). Downstream oxygen saturation is usually observed, and sometimes supersaturation occurs.

In-stream cascades have been built along polluted or eutrophic streams. For example, in Chicago, five reaeration cascades were built recently to reoxygenate the depleted waters of the Calumet waterway. In operation their aeration efficiency (corrected to a temperature of 15°C) is nearly 95% (Robison 1994). Similarly stepped weirs are designed downstream of large dams to control the quality of water releases (e.g., nitrogen supersaturation effect). At Petit-Saut dam, French Guyana,

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[a]January 1999, Vol. 125, No. 1, by Douglas B. Moog and Gerhard H. Jirka (Paper 12867).

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a two-step reaeration cascade was added to reoxygenate the turbined waters, despite the associated energy loss. Reaeration cascades are also used for water treatment. The Montferland plant in the Netherlands was designed to remove nitrate from ground water by sulphur/limestone denitrification. It includes an aeration cascade to reoxygenate depleted waters at the end of the process (Hoek et al. 1992).

New Experimental Data: Aeration Efficiency of Stepped Cascade

A new series of experiments was performed in a flat stepped cascade at the University of Queensland. The 25-m long, 0.5-m wide chute was supplied with a supercritical inflow ($2.5 \le F \le 11$, $H = 0.03$ m) cascading down ten 0.143-m high steps (3.4° mean slope) described by Chanson and Toombes (1997). The distributions of void fraction and bubble counts were recorded with a resistivity probe (inner electrode ∅ 0.35 mm). Measurements were performed on the centerline at 10 longitudinal positions per step. Three steps were investigated at the upstream end, midway, and the end of the chute. The air-water interface area was calculated using (16), and (13) was integrated to predict the aeration efficiency of the cascade. The liquid film coefficient was calculated using Kawase and Moo-Young's (1992) correlations.

The experimental data show depth-averaged specific interface area ranging from 20 to over 120 m^{-1} typically along each step, and maximum bulk specific interface area of up to 160 m^{-1} at the largest flow rate. At each step, the interface area was maximum at the impact of the free-falling nappe and in the following spray region.

The integration of the mass transfer equation (13) yields aeration efficiencies for a single step ranging from 1.5 to 3.5% (in terms of dissolved oxygen) depending upon the flow rate and step location. The strongest aeration is achieved at the largest flow rate. The results imply that the cascade aeration efficiency was about 30 to 40% depending upon the flow rate for a total head loss of 1.4 m only! This highlights the aeration potential of stepped cascades at low to medium flows (e.g., Fig. 7).

FINAL REMARK

Although many researchers including the discussers addressed the effects of air bubble entrainment on water quality, the water quality affects reciprocally the air entrainment processes. The presence of contaminents and chemicals modifies the physical properties of air and water, and hence it could affect the air entrainment processes. Dissolved gas contents might also affect the air entrainment mechanisms. For example, dissolved oxygen content affects the bubble cavitation inception. The discussers believe that dissolved gas might affect the inception of air entrainment in a similar fashion, although no systematic study has been conducted yet.

ACKNOWLEDGMENTS

The discussers acknowledge the assistance of M. Condon and L. Rowlands.

APPENDIX I. REFERENCES

Chanson, H. (1995). ''Predicting oxygen content downstream of weirs, spillways and waterways.'' *Proc., Instn. Civ. Engrs., Water, Maritime & Energy*, London, 112(Mar.), 20–30.

Chanson, H. (1997). ''Measuring air-water interface area in supercritical open channel flow.'' *Water Res.*, 31(6), 1414–1420.

Chanson, H., and Brattberg, T. (1997). ''Experimental investigations of air bubble entrainment in developing shear layers.'' *Rep. CH48/97*, Dept. of Civ. Engrg., University of Queensland, Australia.

Chanson, H., and Toombes, L. (1997). ''Flow aeration at stepped cascades.'' *Res. Rep. No. CE155*, Dept. of Civ. Engrg., University of Queensland, Australia.

Gulliver, J. S. (1990). ''Introduction to air-water mass transfer.'' *Proc., 2nd Int. Symp. on Gas Transfer at Water Surfaces, Air-Water Mass Transfer*, S. C. Wilhelms and J. S. Gulliver, eds., ASCE, New York, 1–7.

Hoek, J. P. van der, Kappelhof, J. W. N. M., and Hijnen, W. A. M. (1992). ''Biological nitrate removal from ground water by sulphur/limestone denitrification.'' *J. Chem. Tech. Biotechnol.*, 54, 197–200.

Kawase, Y., and Moo-Young, M. (1992). ''Correlations for liquid-phase mass transfer coefficients in bubble column reactors with Newtonian and non-Newtonian fluids.'' *Can. J. Chem. Engrg.*, 70(Feb.), 48–54.

Rindels, A. J., and Gulliver, J. S. (1989). ''Measurements of oxygen transfer at spillways and overfalls.'' *St. Anthony Falls Hydr. Lab. Proj. Rep., No. 266*, University of Minnesota, Minneapolis.

Robison, R. (1994). ''Chicago's waterfalls.'' *Civ. Engrg.*, ASCE, 64(7), 36–39.

APPENDIX II. NOTATION

The following symbols are used in this paper:

a = specific interface area (m^{-1});
C = local void fraction;
C_{gas} = local dissolved gas concentration in water (kg/m^3);
d_{ab} = air bubble size (m);
F_{ab} = air bubble count (Hz);
k_L = liquid film coefficient (m/s); and
V = local velocity (m/s).

Closure by Douglas B. Moog,[5] Associate Member, ASCE, and Gerhard H. Jirka,[6] Fellow, ASCE

The discussion of aeration in the presence of ''whitewater'' is most welcome, since it can be an important pathway for gas absorption in channel flow, and it was not covered in depth in the original paper. It was included in that paper in order to describe the observed aeration enhancement by bubble entrainment in experimental runs employing the same bed geometry that did not produce entrainment in less energetic flows, and to provide an analytical expression for that enhancement. That expression was certainly tentative, based on only three points and an observed threshold, but as a starting point it has the advantage of being expressed in terms of an ''element Froude number,'' defined using quantities that could be estimated for a natural stream. Such an expression would be an important step in transferring findings for cascades to reaeration of natural streams.

The main thrust of the paper was to analyze the observed enhancement of aeration for large bed roughness without the presence of air entrainment. Such flows are very common in natural streams, sometimes alternating with whitewater segments, and free surface flux continues even in the presence of whitewater. More fundamentally, the paper provides further support for the small eddy renewal theory, showing how it may explain the enhancement, and pointing out the importance of accounting for the spatial distribution of turbulent energy dissipation in the stream channel. Thus, the writers do feel the paper is very relevant to large-roughness channel flow.

The discussers provided expressions for the specific interfacial surface area, and a version of the gas transfer equation (13) incorporating this quantity. It is certainly a vital factor in gas transfer via air bubble entrainment, and could be used to

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calculate gas fluxes given an appropriate expression for k_L. It should be pointed out that the small eddy model may not be appropriate for this calculation. The support for this model provided by the writers' papers cannot be extended to transfer from bubbles in general [though indeed it was for this case first derived by Lamont and Scott (1970)], because bubbles may be similar in size to or smaller than the dissipative turbulent motions and are thus outside the scope of the theoretical discussion and experimental evidence, which covered only free-surface transfer.

ALLUVIAL FANS FORMED BY CHANNELIZED FLUVIAL AND SHEET FLOW. I: THEORY[a]

Discussion by Emmett M. Laursen,[5] Life Member, ASCE

Alluvial fans are obviously depositional topographical features. All alluvial fans are probably not exactly alike, although there are a number of ways in which they are at least similar. The purpose of this discussion is to add another important characteristic of flow on alluvial fans—at least in the Southwest. Fans there are composed of sediments that are very porous and permeable, and the water table is well below the stream beds. As a result the flow out of the mountain canyon soaks down out of the streambed, and the discharge becomes less and less as the distance from the mountain increases. The reduced discharge cannot transport the initial sediment load; therefore, part of the load (the coarser part) is left behind. Indeed all of the flow can infiltrate, and all of the sediment will then be deposited. The bank height may then be measured in inches, not feet. The next flood, depending on its size, is likely to overtop the banks, flow laterally down the natural levees, and begin to establish a new course.

Storm events downstream of the mountain will cause flow in both the old stream course and the new. The old deposits can be eroded and transported downstream, perhaps to be deposited again; the new course can be enlarged, making it a preferred course. Thus the loss of discharge through infiltration seems, in itself, to be an adequate reason for the avulsions common to alluvial fans. In what flood an avulsion occurs, and where it occurs, offhand appear to be random—although we all could walk the washes and probably agree where we would expect it to happen and how deep the flow would need to be.

One thing clear is that at some time the flow will be anywhere and, eventually, everywhere; the deposits will also be everywhere and the fan will be a cone. (Except when adjacent cones overlap, and the cones become a plain extending out from the mountainside.)

The usual profile for a stream is a curve that is concave upward. This shape is to be expected because the discharge increases down the stream with the increase in watershed area. If the storms always occurred on the mountain, and there was only one watercourse, the limiting shape of the stream profile on the alluvial fan would be concave downward as a steeper slope is required to transport the sediment load with a smaller and smaller discharge.

The slopes of streams in the Southwest, in my experience, are surprisingly steep and surprisingly linear. A combination of concave up and concave down at the same time is bound to be surprisingly linear. (My first experience with stream profiles was as a rodman on a Corps survey crew on the Minnesota River in 1939. Our transitman was not the best and had to take several water surface shots to get one that our recorder would accept. With slopes of 5% and more on tributaries in the Southwest, one doesn't need a transit to see the direction of flow.)

(I also remember the first time I saw the sand beds of the washes extending out from a mountain surrounded by merged alluvial fans from an airplane. These washes ended about halfway down the fans and a new set started between the original set—not quite this simple, but in essence, this simple.)

Closure by Gary Parker,[6] Member, ASCE

The writers appreciate the discussion. The analysis presented in the paper applies to the case for which losses of water due to infiltration can be neglected. This is not always the case, especially in arid environments. S. Tao of our laboratory has performed pilot experiments on the case with large infiltration losses. Large infiltration losses did indeed cause the long profile of the fan to become slightly downward concave rather than upward concave, leaving characteristic deposits at the distal end that R. Hooke has called ''sieve lobes.'' The issue clearly merits further research.

Our results indicate fluvial fan long profiles that are essentially linear in their proximal half and upward concave in their distal half. Such profiles are often observed in nature. The fans with purely linear long profiles are likely dominated by debris flows rather than fluvial transport. Research on dynamic models of debris flow fans is sorely lacking.

The writers would like to mention the following to the discusser and the general readership. The predictive methods of the paper have been reduced to an Excel 5.0 spreadsheet program, ''Acronym6.xls,'' which can be downloaded from the Web site ⟨http//www1.umn.edu/safl⟩. The spreadsheet provides 3D graphical as well as numerical results, and allows for easy application of the theory.

DISPERSION MODEL FOR MOUNTAIN STREAMS[a]

Discussion by Bernhard H. Schmid,[2] Member, ASCE

The author is to be commended for his interesting reanalysis of Day's dispersion data. The paper contains, however, two

[a]October 1998, Vol. 124, No. 10, by Gary Parker, Chris Paola, Kelin X. Whipple, and David Mohrig (Paper 15069).

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[a]February 1999, Vol. 125, No. 2, by Bruce Hunt (Paper 16128).

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points that are in need of clarification and will, therefore, be commented on subsequently.

Under the heading ''Dead-Zone Model'' the author presents the set of the so-called transient storage equations. Following the introduction of the temporal moments of order n, analytic expressions are derived yielding, among others, the temporal variance of the distribution of main stream tracer concentration. This section of the paper concludes with the statement: ''The results of this section, which show that the temporal variance and peak concentration decay rate have behaviors that are similar to the corresponding results for the Fickian model, have not appeared previously in the literature.'' In this context, I find it necessary to draw attention to the work by Nordin and Troutman (1980). They treated the following system of equations:

$$\frac{\partial c}{\partial t} + u \cdot \frac{\partial c}{\partial x} = K \cdot \frac{\partial^2 c}{\partial x^2} + \varepsilon \cdot T^{-1} \cdot (c_d - c) \quad (59)$$

$$\frac{\partial c_d}{\partial t} = T^{-1} \cdot (c - c_d) \quad (60)$$

where c, u, x, and t conform to the definitions given by the author. Recognizing that Nordin and Troutman's K, ε, T^{-1}, and c_d correspond to Hunt's D, α, β, and s, respectively, one can see that the sets of equations (11) and (12) on one hand and equations (59) and (60) on the other are identical.

To avoid confusion, the mathematical symbols used subsequently now will be the same as in the original paper. With this notation, Nordin and Troutman's (1980) relationship for the temporal variance [their Eq. (11)] reads

$$\sigma_t^2 = \left(\frac{x}{u} + \frac{4D}{u^2}\right) \cdot 2D \cdot \frac{(1+\alpha)^2}{u^2} + \left(\frac{x}{u} + \frac{2D}{u^2}\right) \cdot 2\,\frac{\alpha}{\beta} \quad (61)$$

Rearrangement of terms yields

$$\sigma_t^2 = \left[(1+\alpha)^2 + \frac{\alpha \cdot u^2}{\beta \cdot D}\right] \cdot \frac{2 \cdot D \cdot x}{u^3} + \frac{8 \cdot D^2}{u^4} \cdot (1+\alpha)^2 + 4 \cdot \frac{\alpha \cdot D}{\beta \cdot u^2} \quad (62)$$

For comparison, (26) of the original paper can be reproduced as

$$\sigma_t^2 = \left[(1+\alpha)^2 + \frac{\alpha \cdot u^2}{\beta \cdot D}\right] \cdot \frac{2 \cdot D \cdot x}{u^3} + \frac{8 \cdot D^2}{u^4} \cdot (1+\alpha^2) + 4 \cdot \frac{\alpha \cdot D}{\beta \cdot u^2} \quad (63)$$

Clearly, the author's (26) nearly agrees with Nordin and Troutman's (11), written here as (62) after some arithmetic rearrangement (but without any introduction of further assumptions, order-of-magnitude arguments, or suchlike). As both of the above relationships relate to the same initial boundary value problem, the corresponding results should not only agree nearly, but completely. In this context, I checked the author's (24*b*), which is the parent equation of (26). This expression is correct, though not new [it follows quite simply from Nordin and Troutman (1980) and Schmid (1995)]. Further straightforward arithmetic revealed (62) above to be correct, whereas the author's (26) contains a writing error. The second term on the right-hand side should read

$$\frac{8 \cdot D^2}{u^4} \cdot (1+\alpha)^2$$

instead of

$$\frac{8 \cdot D^2}{u^4} \cdot (1+\alpha^2)$$

A further point to be addressed in this discussion concerns the author's statement that an analytical solution to the system of the dead-zone equations is unavailable. The validity of this statement depends on how exactly an analytical solution is defined, but it is worth mentioning that considerable progress has been made recently [e.g., Hart (1995) and Schmid (1997)] so that expressions are indeed available now that in a sense may be termed ''analytical solutions'' (and can, for instance, be used to check on temporal moments derived from other sources, as has been done with success).

APPENDIX. REFERENCES

Hart, D. R. (1995). ''Parameter estimation and stochastic interpretation of the transient storage model for solute transport in streams.'' *Water Resour. Res.*, 19(3), 718–724.

Nordin, C. F., and Troutman, B. M. (1980). ''Longitudinal dispersion in rivers: The persistence of skewness in observed data.'' *Water Resour. Res.*, 16(1), 123–128.

Schmid, B. H. (1995). ''On the transient storage equations for longitudinal solute transport in open channels: Temporal moments accounting for the effects of first-order decay.'' *J. Hydr. Res.*, Delft, The Netherlands, 33(5), 595–610.

Schmid, B. H. (1997). ''Analytic solution of the transient storage equations accounting for solute decay.'' *Proc., Theme B*, 27th IAHR Congr., Vol. 1, Delft, The Netherlands, 15–20.

Closure by Bruce Hunt[3]

The writer thanks the discusser for including some additional references and for calling attention to an error that was made when (26) in the writer's original calculations were transcribed to the manuscript. Eq. (62), which is the corrrected form (26), does indeed appear in Nordin and Troutman. However, this error has no effect upon the leading term of the asymptotic behavior for the temporal variance, and the important end result that asymptotic peak decay rates for both Fickian and dead-zone models are proportional to $1/\sqrt{x}$ is unchanged. This result is not given by Nordin and Troutman, and it is important because Day's results show that experimental peak decay rates are much closer to being proportional to $1/x$, which agrees with the solution of (27).

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