## SEDIMENT TRANSPORT INDUCED BY RAINDROPS IMPACTING SHALLOW FLOWS

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#### ABSTRACT

A theory for RIFT, the transport process that results from raindrops impacting shallow flows, is presented. The theory relies on the observation that, after being lifted from the soil surface, a particle moves downstream a distance that depends on flow velocity and the time the particle remains suspended in the flow. The theory indicates that sediment transport rates increase linearly with rainfall intensity and flow velocity when entrainment by flow is absent.

Laboratory experiments where sand was eroded by rain-impacted flow provide support for the theory. In addition to influencing the downstream motion of particles detached by raindrop impacts, surface-water flows absorb raindrop energy. Consequently, interactions between flow depth and drop size were also examined through the laboratory experiments. This resulted in a mathematical model of RIFT that accounts for the interactions between raindrops and flow on the sediment transport rate. When applied to experimental data, the model showed that the time-averaged effect of rainfall on sediment transport by rain-impacted flow is independent of the manner by which the rain is applied.

Particle size was also varied in the experiments. Particles having similar fall velocities in water but different densities were transported at different rates. The differences were more the result of differences in the masses of material lifted into the flow by a drop impact than differences in the distances the particles travelled after being disturbed.

On soil surfaces, pre-detached particles stored on the surface between impacts protect the soil matrix. Using a numerical model of RIFT, the protective effect was shown to vary in time, with particle size and with the difficulty experienced by drops in detaching soil particles from the soil matrix.

Flow depths and velocities are seldom measured but the RIFT theory provides a mechanism for developing models using more commonly measured parameters. An analysis of field experiments using an alternative to the more commonly used interrill erosion model indicates that actual interrill erodibilities may differ significantly from those determined using the previous model. An alternative to the EI<sub>30</sub> index in the USLE also results from the RIFT theory.

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### CERTIFICATE

I certify that the substance of this thesis has not already been submitted for any degree and is not being currently submitted for any degree.

I certify that any help received in preparing this thesis, and all sources used, have been acknowledged in this thesis.



#### PREFACE

The work reported in this thesis results from a long term interest in erosion resulting from raindrop impact. Initially, when I joined the CSIRO Division of Soils 1969, I worked on splash erosion and acoustic impact as a measure of the erosive power of rainfall. When the raintowe: facilities of the Division became fully operational in the mid 1970s, as part of the Sediment Transport Group, I was involved in performing some initial laboratory experiments on sediment transport by rain-impacted flow before undertaking experiments with runoff and soil loss plots under natural rainfall. Erosion by rain-impacted flow was the major cause of the erosion in these field experiments and it soon became obvious that internationally there was a lack of knowledge on this erosion process. Most of mathematical models of rainfall erosion produced to date fail to account for sediment transport by rainimpacted flow because of this. The work reported here is a contribution towards resolving this problem.

Most of the work reported here was done at the Canberra Laboratories of the CSIRO Division of Soils. In regard to this work, the assistance of Colin McLachlan, Joseph Kemei and Neville Carrigy who helped from time to time with some of the experiments is gratefully acknowledged. Some of the statistical procedures used in this thesis result from work done by Dr. Jeff Wood (I.N.R.E. Biometric Unit, CSIRO). The assistance of Dr. David Smiles, Dr. Pat Walker, Dr. John Williams in providing an administrative climate which allowed the work to proceed is also gratefully acknowledged. The quality of the figures in this thesis is a testament to the skills of the Division's Drawing Office in Adelaide. Also, a special vote of thanks is extended to John Hutka who undertook much of the work in developing the raintower facilities back in the mid 1970s. Without the development of such facilities, much of the work reported here would not have been possible.

The work covering drops with low impact velocities was done at the Department of Resource Engineering, University of New England with the assistance of a CSIRO/UNE co-operative grant. This work required the development of new facilities at the university. The support of the workshop staff of the Department of Resource Engineering, in particular David Sauer and

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Trevor Stace, in developing these facilities is gratefully acknowledge. My thanks are also given to Prof. John Burton (Dept. Res. Eng., UNE), Dr. Alf Cass (Dept. Agron. and Soils, UNE) and Prof. Ian Moore (CRES, Australian National University) who acted as supervisors for the Ph.D program.

#### SUMMARY

Rain-impacted flows often dominate the sheet and inter-rill erosion environment, but the factors that influence sediment transport by these flows have been studied little. Many modern models of rainfall erosion ignore the contribution rain-impacted flows make to the movement of soil material over the soil surface. In this thesis, a theoretical basis for investigating the factors that influence sediment transport by rain-impacted flow is presented in Chapter 2. The effects of a number of these factors are studied experimentally in Chapter 3. Then the application of the theory to modelling the erosion of soil surfaces by rain-impacted flow is demonstrated in Chapters 4 and finally, some suggestions for further study are presented in Chapter 5.

When a soil particle is detached from the soil matrix by a raindrop impacting a shallow flow, the particle may move downstream across an arbitrary boundary in one of 4 modes. The particle may move aerially by drop splash, but if it fails to be lifted above the water surface, or falls back into the water upstream of the boundary, it may then move in one of 3 modes that are associated with the flow. It may, if it is small or of low density, move as suspended load. If it is larger or of higher density, it will fall back to the soil surface before the boundary. If the flow has sufficient velocity, the particle may then be entrained by the flow. If not, then the subsequent downstream movement can only occur under the stimulus of a external force. Raindrops impacting shallow flows can provide that force.

The downstream movement of soil particles that relies on repeated stimulation by raindrop impact is termed Raindrop Induced Flow Transport (RIFT). The theory for RIFT presented in this thesis relies on the observation that, after being lifted from the soil surface as a result of a drop impact, a particle travels a distance  $(x_p)$  downstream that depends on the time the particle remains suspended in the flow  $(t_p)$  and the velocity of the flow (u). The distance travelled controls the extent of a zone, called the active zone, in which all drop impacts cause soil material to pass across the boundary. As a result, the sediment transport rate  $(q_{sR})$  across the boundary is given by the product of the frequency (f) of the drop impacts in this zone and the mass of material (D) each drop lifts into the flow. The sediment transport rate can

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be expressed as a function of rainfall intensity (R), raindnop size (d) particle size (p) and flow velocity by

$$q_{sR}(p,d) = \frac{6 R_d t'_{pd} u D_{pd}}{\pi d^3}$$
(2.20)

where  $t'_{pd}$  is the effective average duration of the suspension of p sized particles induced by the impact of drops of size d.

On soil surfaces, pre-detached particles are stored on the soil surface between impacts and, as a result, drop impacts may lift both pre-detached particles and particles from the soil matrix. Pre-detached particles sitting on the surface are lifted first and particles from the soil matrix are lifted only if there is excess energy left after this process. The pre-detached particles provide a degree of protection (H), with the result that

$$D_{pd} = H.D_{pd,D} + (1-H)D_{pd,M}$$
 (2.24)

where  $D_{pd,D}$  is the value of  $D_{pd}$  obtained when the soil matrix is completely protected and  $D_{pd,M}$  is the value of  $D_{pd}$  obtained when no pre-detached material exists. The need to store particles on the soil surface during the transport process results in the development of a layer of pre-detached particles on the soil surface. Through the use of a numerical model of the RIFT processes, the temporal and spatial variability of this layer is demonstrated in Section 2.4.

Available data, together with new data collected during this study (Chapter 3), confirm that Eq. 2.20 can account for effects of R and u on  $q_{sR}$ . These data also show that  $q_{sR}$  is influenced by particle size, density and flow depth (h). Apart from drop size and particle size, factors such as drop velocity, drop shape, particle density, and flow depth influence  $D_{pd}$  and t'pd. The data collected during the study show that,

$$D_{pd}t'_{pd} = k_0(1 - \beta h)$$
 for  $h_1 < h < h_2$  (3.5)

where  $h_1 \approx 4 \text{ mm}$  and  $h_2 \approx 3d$ ,  $k_0$  is the intercept on the "y" axis projected by the linear equation

$$D_{pd}t'_{pd} = k_0 - b_2h \tag{3.6},$$

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and  $\beta$  is the inverse of the projected intercept on the "x" axis. Both  $\beta$  and  $k_0$  vary with drop size and velocity but  $\beta$  varies independently of the characteristics of the eroding surface.  $k_0$  is influenced by both the drop and the surface characteristics and  $k_0$  decreases in value with particle fall velocity to a power less than 0.5 when particle size varies.

In this study, coal was used to examine the movement of particles of a density similar to that of aggregates. The experiments show that Eq. 3.5 applies not only to sand but also to coal but, when the particles have similar fall velocities,  $q_{sR}$  for coal particles greatly exceeded the values for sand. Eq. 3.5 is also valid for erosion of soil surfaces by rain-impacted flows where a wide range of particle size and density are present.

It follows from the combination of Eqs. 2.20 and 3.5 that the effects of rain (r), flow and soil (s) on  $q_{\rm SR}$  can be represented by an equation of the form

$$q_{sR}[s,r] = k_s R u f[h,r]$$
 (3.21)

where  $k_{\rm S}$  is the susceptibility of the soil to erosion by rain-impacted flow and  $f[{\rm h},r]$  is a function that accounts for the interaction between raindrop size and flow depth. Analysis of the data from the experiments presented here, together with the data from Moss and Green (1983), indicates that raindrop size has a non-significant influence on  $q_{\rm SR}$  when medium-to-large drops travelling at or close to their terminal velocities impact flows shallower than about 4 mm. Evidently, this effect results from the water surface restricting the height to which particles are lifted in the flow when these high energy drops impact shallow flow because drop size influences  $q_{\rm SR}$  when small drops travelling at terminal velocity, and medium-to-large drops travelling at subterminal velocity, impact flows shallower than 4 mm. On the basis of the apparent constraint placed on  $q_{\rm SR}$  by the height of the water surface, the  $q_{\rm SR}$ -h relationship observed for 5.1 mm drops travelling at terminal velocity,

 $q_{sR}[s,r] = 0.001553 k_s R u h exp(5.7975 - 0.1881h),$ 

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provides a mechanism for determining the upper limit of  ${\rm q}_{\rm SR}$  for flows shallower than about 20 mm. The above equation results from

$$k_{\rm s} f[{\rm h,d}] = {\rm h} \exp(5.7975 - 0.1881{\rm h})$$
 (3.26a)

and the observation that, for 0.2 mm sand used in the experiments,  $k_S = 644$  kg.s m<sup>-3</sup> (Table 3.7).

In that, at some critical depth  $(h_c)$ , the f[h,d] to h relationship departs from Eq. 3.26a, Eq. 3.26a is applies when  $h \le h_c$ , and, for 0.2 mm sand,

$$k_{\rm s} f[{\rm h,d}] = {\rm h} \exp(5.7975 - 0.1881{\rm h_c} - {\rm b'_d}({\rm h-h_c}))$$
 (3.26b)

where

$$b'_d = \exp(0.77749 - 0.48251 d)$$
 (3.27)

applies when  $h < h_c$ . Together, Eqs. 3.21 ,3.26 and 3.27 provide a mechanism for estimating the effect of drop size - flow depth interaction for rain with nonuniform drop-size distributions, and a mechanism for separating the erosivity and erodibility components in erosicn by rain-impacted flow. Using this mechanism, the assumption that the time averaged effect of rainfall on sediment transport by rain-impacted flow is independent of whether rain is applied as a pulse, as often the case with field rainfall simulators, or applied as a continuous stream, as in the case of natural rainfall, was found to be valid (Section 4.2). However, the effect of pulsed rainfall on variations in the susceptibility of surfaces to erosion lies outside the scope of this study.

While factors such as flow depth (h) and velocity (u) directly affect  $q_{sR}$ , they are seldom measured. It is well known that sediment discharge is given by the product of flow discharge ( $q_w$ ) and sediment concentration (c). Thus

$$q_{sR} = q_w c_R \tag{4.5}$$

where  $c_R$  is the sediment concentration resulting from the raindrops impacting the flow. Since flow discharge is the product of flow depth and velocity, it follows from Eq. 3.21 that

$$c_{R}[s,r] = k_{s} R f[h,r] h^{-1}$$
(4.6)

and

$$q_{sR} = k_s q_w R f[h,r] h^{-1}$$
 (4.7)

Considering  $q_{SR}$  in terms of flow discharge thus eliminates the need to consider flow velocity but the effect of flow depth remains to be accounted for. However, it is also well known that slope gradient (S) influences flow depth and velocity and, as a result, Eq. 4.7 can be rewritten as

$$q_{SR} = k_1 q_W R f[S]$$
(4.8)

where f[S] is a function that accounts for the effect of slope gradient on  $q_{SR}$  and  $k_1$  is a coefficient influenced by variations in soil characteristics and also by variations in flow depth that are not accounted for directly by f[S]. Analysis of data from Meyer and Harmon (1989) shows that, for S<30%,

f[S] = S (4.9) but other functions that include an interaction between soil and slope gradient may be more appropriate (Section 5.2).

Equation 4.8 is comparable to a widely used model that uses  $R^2$  rather than R q<sub>w</sub>, and K<sub>i</sub> rather than k<sub>1</sub>. Analysis of 18 cropland soils used in the USDA Water Erosion Prediction Project (WEPP) in terms of the two models indicates that the susceptibility of some soils to erosion by rain-impacted flow may differ substantially from the values used in WEPP (Section 4.1).

The dynamic depositional layer (DDL), the layer that results from the need to store particles on the soil surface between drop impacts when RIFT operates and entrainment by flow is absent, has a major influence on sediment discharge through the term H in Eq. 2.24. While the development and effect of the DDL is demonstrated using a numerical model of the RIFT processes in Section 2.4, the modelling concepts used in that section are impractical for field sized areas. In Chapter 5, an alternative approach is suggested. This approach considers the particle uplift and deposition events separately during an element of time, and the protective effect of the DDL to be absolute (H=1)

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when the mass of the DDL in the active zone associated with any particle is greater or equal to the maximum mass RIFT can transport from that zone during that element of time. Otherwise, H is given by the ratio of the mass of the DDL in the active zone and the maximum mass RIFT can transport from that zone during that element of time. While the model produces reasonable results under a set of arbitrary conditions, the concepts need to be evaluated under more realistic circumstances.

Just as the consideration of the product of flow discharge and sediment concentration provides an alternative interrill erosion model to the one used in WEPP, so too does this product provide an alternative to the  $EI_{30}$  index in the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE). In this case, the product of flow discharge, or its surrogate, the excess rate of rainfall, and the rate of expenditure of rain kinetic energy may be considered as a more processed orientated index than E30. Also, the use of such an index would enable factors, such as antecedent soil moisture, that have important impacts on soil losses from individual rain storms but which are currently ignored in the USLE and RUSLE, to be taken into account. While soil erodibilities would need to be re-evaluated if  $\text{EI}_{30}$  is replaced by this product, many of the algorithms and procedures for determining the effect of other factors, such as vegetative cover and changes in soil organic matter, that are currently part of the USLE and RUSLE could be retained. Under these circumstances, the model could perhaps fill the void between the USLE and WEPP models that will almost certainly exist in many parts of the world as a result of the extensive data requirements of WEPP.

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#### Table 3.1.

Conditions used in the current experiments. x' denotes the factor being investigated, s denotes experiments in which the rainfall modules were kept static. The values in brackets in column 2 are the levels at which the respective factor was held constant.  $R_d$  was nominally 64 mm h<sup>-1</sup> except where x=R\_d.

## Table 3.2.

Regression analysis for the effect of rainfall intensity ( $R_d$ , mm h<sup>-1</sup>), flow velocity (u, mm s<sup>-1</sup>) and flow depth (h, mm) on the sediment transport rate ( $q_{sR}$ , g m<sup>-1</sup> s<sup>-1</sup>) for p=0.2 mm, d=2.7 mm and F=11.2 m. The values in brackets in column 2 are the levels at which the respective factor was held constant. NB. The values of u and h were maintained within 5 % of the numbers shown in parenthesis.  $R_d$  values when u,h = constant varied considerably. For  $R_d$ , the values in parenthesis are nominal.

#### Table 3.3

(A). Regression analysis for the effect of flow depth (h) on  $D_{pd}t'_{pd}$  for sand of various particle size (p) for flows impacted by 2.7 mm drops after falling from 11.2 m.

(B). Regression analysis for the particle size on  $k_0$  for sand under flows impacted by drops of various size (d) after falling from 11.2 m

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and the closest containers. Row 4 is the row closest to the downstream end of the target.

Table 5.1.

Spatial variations in particle size distribution ( expressed proportions of the total mass) and the protective effect of the DDL (H) produced by the model in Appendix III

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#### LIST OF SYMBOLS

- $\alpha_1$  Ratic of concentration of ith size class next to bed to mean concentration over entire depth
- $\beta$  A coefficient (=b2k<sub>0</sub><sup>-1</sup>)
- $\beta_d$  A coefficient dependent on d
- $\chi$  ratio of the terminal velocity of fall of a particle in water (vp) to its average velocity of fall through a flow.

### a Detachability coefficient

- $a_S$  a coefficient influenced by soil characteristics
- a<sub>D</sub> a for deposited layer
- a<sub>M</sub> a for soil matrix
- a<sub>X</sub> Either a<sub>D</sub> or a<sub>M</sub>
- a<sub>D</sub>\* Value of aD below critical flow depth (h\*)
- a<sub>1</sub> Coefficient

#### b A power

- b<sub>1</sub> Coefficient
- b<sub>2</sub> Coefficient in D<sub>pd</sub>t'<sub>pd</sub> to h relationship
- $b_s$  a coefficient influenced by soil characteristics
- b'd A coefficient dependent on d

c Sediment concentration

- c; Sediment concentration of ith size class
- $c_R$  Sediment concentration produced by RIFT
- C<sub>e</sub> Fraction of soil unprotected from drop impact

#### d Drop size (mm)

di	Sediment deposition rate for ith size class
Dpd	Mass of p sized particles lifted by a d sized drop
D <sub>pdz</sub>	Mass of p sized particles lifted to height z by a d sized drop
DDL	Dynamic depositional layer resulting from the need for storage

of material on the surface between drop impacts

e; Rainfall detachment rate for ith size class

- f[h,d] Function accounting for the interaction between drop size
   and flow depth (0-1)
- f[S] Function accounting for the effect of slope gradient in a interrill erosion model
- $f_{\rm d}$   $\,$  Frequency of impacts of drop size d within  $x_{\rm pz}\text{-}0.5x_{\rm cz}$  upstream of a boundary
- fp Dpd.M-to-Dpd.D ratio
- f<sub>S</sub> Factor accounting for departures from f[S]=S
- F Distance of drop fall
- F<sub>d</sub> Spatially averaged impact frequency of d sized drops

h Flow depth (mm)

- H Coefficient of protection of matrix soil by deposit
- $h_{\mbox{Od}}$  Flow depth for no RIFT projected for drop size d by linear  $q_{\rm SR}$  to h relationship
- h<sub>C</sub> The critical flow depth where the depth of flow does not constrain the height to which particles are lifted

I Number of sediment size classes

К	Coefficient in relationship between T and R $% \left( {{{\boldsymbol{x}}_{i}}} \right)$
k <sub>0</sub>	Constant in linear D <sub>pd</sub> t' <sub>pd</sub> to h relationship
k <sub>0d</sub>	Constant influenced by d
k <sub>p</sub>	Coefficient varying with particle size
k <sub>s</sub>	Coefficient dependent on soil properties
k <sub>1</sub>	Coefficient depending on $\boldsymbol{k}_{\mathrm{S}}$ and a number of other factors
k'pd	Constant dependent on particle and drop size
k'd	Factor accounting for drop size contributions to k'pd
k'p	Factor accounting for particle size contributions to k'pd

- L Loss of sand relative to loss at position 17
- $L_{m}$  Mean of L
- $L_x$  Length of a plane surface

 $M_{\mbox{Dz}}$   $\,$  Mass of particles lifted to height z  $\,$ 

- N Number of drop sizes
- n Variable in summation equation
- p A power in e<sub>i</sub> to R relationship
- p particle size (mm)
- p<sub>m</sub> Drop momentum
- ${\rm P}_{max}$  Peak pressure exerted at the point on the bed below the centre of a drop impact
- $P_{pD}$  Proportion of p sized particles in DDL
- ${\tt P}_{pM}$  . Proportion of p sized particles in soil matrix
- Q Rain induced discharge per unit area
- q<sub>S</sub> Rate sediment transported by flow across a unit width of a boundary
- q<sub>SO</sub> Mass of material transported across the downstream boundary
   of an element
- q<sub>SOD</sub> Mass of material from DDL transported across the downstream boundary of an element
- q<sub>soM</sub> Mass of material soil matrix transported across the downstream boundary of an element
- $q_{sR}$   $q_s$  for sediment transported by RIFT
- q<sub>w</sub> Rate at which water is discharged across a unit width of a boundary

R Rainfall intensity

- R<sub>d</sub> Intensity of rain of drop size d
- r; Sediment entrainment rate for ith size class

S Slope gradient

### т Rate at which sediment is transported across a boundary Rate at which splash transports sediment across a boundary $T_A$ Rate at which bed load is transported across a boundary $T_{R}$ Rate at which rain-impacted flow transports sediment $T_{F}$ across a boundary Rate at which suspended load is transported across TS a boundary Rate at which RIFT transports sediment across a boundary $T_R$ Time p sized particle remains suspended following tp disturbance by a drop impact Time p sized particle remains suspended after being lifted tpz to a height z t'pd Average time p sized particle remains suspended following disturbance by a drop impact

u Flow velocity

- w A power in the relationship between T and R  $W_{\rm f}$  Width of flow
- X Parameter related to stress applied by impacting drop
- X<sub>C</sub> Critical value of X below which particles are not lifted into the flow by a drop impact

x Distance x<sub>cz</sub> Diameter of particle cloud at height z x<sub>p</sub> Distance travelled by a particle of size p x<sub>pz</sub> Distance travelled by a particle of size p lifted to height z x'<sub>pd</sub> Average distance travelled by a particle of size p disturbed by the impact of a d sized drop

z Height from bed

LIST OF EQUATIONS

$$T_{\rm F} = T_{\rm S} + T_{\rm B} + T_{\rm R}$$
 (1.1)

$$T = T_F + T_A = T_S + T_B + T_R + T_A$$
 (2.1)

$$T = K R^{W}$$
(2.2)

$$q_{\rm S} = q_{\rm W} c \tag{2.3}$$

$$\frac{\partial}{\partial x}(q_W c_1) + \frac{\partial}{\partial t}(hc_1) = e_1 - d_1 + r_1 \qquad (2.4)$$

$$e_{i} = a C_{e} \frac{R^{p}}{I}$$
(2.5)

$$d_{i} = v_{i}c_{i} \tag{2.6}$$

$$a C_e R^p$$

$$c_i = ------ (2.7)$$

$$I(Q + v_{i})$$

$$a = H a_{\rm D} + (1-H) a_{\rm M}$$
 (2.8)

$$a_{\rm X} = a_{\rm X} \star (h_{\star} h^{-1})^{b}$$
 (2.9)

$$c_{i} = \frac{a_{D} \star h_{\star} b_{R} p}{1}$$
(2.10)

$$h^{D} \sum_{i=1}^{\Delta_{i}v_{i}}$$

$$t_p = h v_p^{-1}$$
 (2.11)

$$x_p = t_p u \tag{2.12}$$

$$t_p \approx t_{pz} = z v_p^{-1}$$
 (2.13)

$$M_{Dz} [p,d] = f_d D_{pdz}$$
(2.14)

$$M_{Dz} [p,d] = F_d x_{pz} D_{pdz} W_f$$
(2.15)

$$M_{Dz} [p,d] = \frac{6 R_d x_{pz} D_{pdz} W_f}{\pi d^3}$$
(2.16)

$$M_{Dz} [p,d] = \frac{6 R_d t_{pz} u D_{pdz} W_f}{\pi d^3}$$
(2.17)

$$M_{D} [p,d] = \frac{6 R_{d} t'_{pd} u D_{pd} W_{f}}{\pi d^{3}}$$
(2.18)

$$t'_{pd} = \frac{\int_{0}^{zh} (t_{pz} D_{pdz}) dz}{D_{pd}}$$
(2.19)

$$q_{sR} [p,d] = \frac{6 R_d t'_{pd} u D_{pd}}{\pi d^3}$$
(2.20)

$$c_{R} [p,d] = \frac{q_{sR} [p,d]}{q_{W}} = \frac{6 R_{d} t'_{pd} D_{pd}}{\pi d^{3}h}$$
(2.22)

$$c_{i} (d) = \frac{{}^{6} R_{d} t'_{pd} D_{pd}}{\pi d^{3} h}$$
(2.23)

$$D_{pd} = H.D_{pd.D} + (1-H)D_{pd.M}$$
 (2.24)

$$q_{sR} (p,d) = F_d x'_{pd} D_{pd}$$
(2.25)

$$D_{pd}t'_{pd} = \frac{q_{sR}[p,d] \pi d^3}{6 R_d u}$$
(3.1a)

$$D_{pd}t'_{pd} = \frac{c_{R}[p,d] \pi d^{3} h}{6 R_{d}}$$
(3.1b)

$$D_{pd}t'_{pd} = a_1 d^{3.48}$$
(3.2)

$$D_{pd}t'_{pd} = 0.372 h^{b}I$$
(3.3)  

$$b_{1} = 9.59 \log_{10}(d) - 10.29$$
(3.4)  

$$D_{pd}t'_{pd} = k_{0}(1 - \beta h)$$
(3.5)  

$$D_{pd}t'_{pd} = k_{0} - b_{2}h$$
(3.6)  

$$\beta = \frac{b_{2}}{k_{0}}$$
(3.7)  

$$\beta = 0.175 - 0.0260 d$$
(3.8)  

$$\log k_{0} = -0.507 - 0.616 \log p + 2.24 \log d$$
(3.9)  

$$\log k_{0} = -1.301 - 0.465 \log v_{p} + 2.24 \log d$$
(3.10)  

$$k_{0} = 2.67v_{d} - 8.07$$
(3.11)  

$$\beta = 0.197 - 0.0118v_{d}$$
(3.2)

$$\beta = 0.0852 - 0.00442v_{\rm d} \tag{3.13}$$

$$\log k_0 = 7.543 - 0.4652 \log v_p + 0.7025 \log p_m$$
(3.14)

$$\beta = 0.1104 - 0.001166 p_{\rm m} \tag{3.15}$$

$$x'_{p} = \frac{\prod_{n=1}^{15} (L_{n} \cdot x_{pn})}{L_{m}}$$
(3.16)

$$D_{pdt'pd} = k'_{pd} (1 - \beta_{dh})$$
 (3.17)

$$D_{pd}t'_{pd} = k'_{p}k'_{d} (1 - \beta_{d}h)$$
(3.18)

$$q_{sR} [p,d] = \frac{6 R_d u k' p' d[1 - \beta_d h]}{\pi d^3}$$
(3.19)

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$$c_{\rm R} [p,d] = \frac{6 R_{\rm d} k' p' d [h^{-1} - \beta_{\rm d}]}{\pi d^3}$$
(3.20)

 $q_{sR}[p,d] = k_s R u f[h,d]$  (3.21)

$$f[h,d] \approx 1 - \beta_d[h-h_x]$$
 ,  $h_x < h < 3d$  (3.22)

$$B_{\rm d} = 0.3119 - 0.0507 {\rm d}$$
 ,  $r^2 = 0.986$  (3.23)

$$k_{\rm s} f[{\rm h},{\rm d}] = \frac{q_{\rm sR}[{\rm p},{\rm d}]}{R \,{\rm u}}$$
 (3.24)

$$h_c = 1.74768 + 2.88237 \log(d)$$
 (3.25)

$$k_{\rm S} f[{\rm h,d}] = {\rm h} \exp[5.7975 - 0.1881{\rm h}]$$
 ,  ${\rm h} \le {\rm h}_{\rm C}$  (3.26a)

$$k_{s}f[h,d] = h \exp[5.7975 - 0.1881h_{c} - b'_{d}(h - h_{c})]$$
 , h>h<sub>c</sub> (3.26b)

$$b'_d = \exp[0.76649 - 0.48251 d]$$
 (3.27)

$$f[h,r] = \frac{\sum_{n=1}^{N} (f[h,d]R_d)_n}{\sum_{n=1}^{N} (R_d)_n}$$
(3.29)

$$k_{\rm s} = \frac{q_{\rm sR}[{\rm s}, {\rm r}]}{\frac{{\rm R} \ {\rm u} \ f[{\rm h}, {\rm r}]}{{\rm R} \ {\rm u} \ f[{\rm h}, {\rm r}]}}$$
(3.30)

$$D_{i} = K_{i} R^{2} S_{f}$$

$$(4.1)$$

$$S_{f} = 1.05 - 0.85 \exp \{-4 \sin (\phi)\}$$
 (4.2)

$$D_{i} = q_{sR} L_{x}^{-1}$$
 (4.3)

$$K_{i} = \frac{q_{SR}}{L_{x} R^{2} [1 - 0.85 \exp \{-4 \sin (\phi)\}]}$$
(4.4)

$$\begin{aligned} q_{SR} &= q_w c_R & (4.5) \\ c_R(s, r) &= k_S R f(h, r) h^{-1} & (4.6) \\ q_{SR} &= k_S q_w R f(h, r) h^{-1} & (4.7) \\ q_{SR} &= k_1 q_w R f(S) & (4.8) \\ f(S) &= S & (4.9) \\ q_{SR} &= k_1 q_w R S & (4.10) \\ k_1 &= \frac{q_{3R}}{Rq_w S} & (4.10) \\ k_1 &= \frac{q_{3R}}{Rq_w S} & (4.12) \\ r_S &= \frac{q_{3R}}{k_1 R S q_w} & (4.12) \\ r_S &= \frac{q_{SR}}{k_1 R S q_w} & (4.13) \\ r_S &= \frac{c_R}{k_1 R S q_w} & (4.13) \\ r_S &= \frac{c_R}{k_1 R S} & (4.15) \\ S_L &= 277.18 - 149.16 D_{wSa} + 19.41 D_{wSa}^2 & r^2 = 0.957 & (4.16) \\ Q &= 9.02 + 0.918 D_{wSa} - 1.2385 D_{wSc}^2 & r^2 = 0.956 & (4.17) \\ \frac{q_{3R}}{r_u} &= k_S f(s, r) & (4.18) \\ q_{SO}(p) &= R P_{DD} k_P R u f(h, r) W_f & (5.2) \\ q_{SOM}(p) &= f_p (1-H) P_{pM} k_P R u f(h, r) W_f & (5.3) \end{aligned}$$

$[S] = a_{S} + b_{S}S$		(5.4)
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$$f[S] = \exp((a_s + b_s S))$$
 (5.5)