HYDRAULICS RESEARCH DIVISION

Technical Note

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TITLE: "An Automatic Instrument for Long Term Littoral Zone Measurements"

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REASON FOR REPORT: This report has been prepared in response to Dr. Sly's request of March 19, 1980 to the Hydraulics Research Division for advice on the methodology of unattended wave measurement in littoral areas which are or are likely to be suitable sites for fish spawning.

CORRESPONDENCE FILE NO:

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ABSTRACT

This paper addresses the problem of making in situ measurements of causes and effects related to sediment transport in the littoral zone. The primary causes of sediment movement (waves, currents) occur on time scales of seconds or minutes, while significant topographic modifications are associated with time scales of weeks or months. Recognition of this large difference in time scales between measurable cause and observable effect leads to consideration of an instrument which will obtain average characteristics of waves, currents and sediment transport at regular intervals over long periods of unattended operation. The heart of the proposed instrument is a commercially available integrating digital recorder which will average analog signals over some pre-set time, record the averages in digital form and repeat the process at regular pre-set intervals. Wave and mean water level information would be obtained from a pressure transducer through the averages of the pressure signal itself and those of the root mean square of its fluctuations and of the time derivative of its fluctuations. New sensors for the measurement of drift current velocity components and suspended sediment transport are proposed. The former would employ a heated element differential technique and the latter a "differential sediment interceptor". Methods of detecting longshore and shore-normal movement and the angle of approach of the waves are discussed. Finally, a suggestion for sensing bed load movement is put forward.

1.0 INTRODUCTION

This report has been prepared in response to Dr. Sly's request of March 19, 1980 to the Hydraulics Research Division for advice on the methodology of unattended wave measurement in littoral areas which are or are likely to be suitable sites for fish spawning. Dr. Sly also asked for an estimate of the cost of a single system which would provide information on the near-bottom wave action during significant storms. This last request for cost estimates demands a rather more specific approach with regard to the equipment which would be employed rather than merely the outline of a concept.

This technical note takes the approach that a specific solution to the particular problem outlined by Dr. Sly would be so little different from a general purpose automatic littoral zone sampler that it is the design of the latter which is worth pursuing strictly from a long term cost/benefit point of view.

2.0 WAVE MEASUREMENT

Let us first examine the question of wave measurement. As is common in such research, the requirement is for average wave parameters such as significant wave height and period.

As proposed by Donelan (1976) and later implemented through SSD and an outside contractor, the desired mean parameters may be deduced from the mean square of the surface deviation $\overline{\eta^2}$ and that of its time derivative $\overline{\eta_t^2}$. Unfortunately, the small depth, possibility of icing and unattended long term operation preclude the possibility of a surface wave sensor. It would seem that the only practical sensor would be a bottom-mounted one. The difficulty here is that all measurable wave effects are attenuated with depth by a factor which is dependent on the depth/wave length ratio. For brevity of expression, we shall select the pressure as the effect of interest although a similar approach can be applied to the velocity field. Pressure is an easily measured scalar and is, in fact, the parameter most frequently used to detect the passage of waves in shallow water.

Linear theory yields the pressure on the bottom $p_{(t)}$ in terms of the surface deviation $\eta_{(t)}$:

$$\frac{p_{(t)}}{\eta_{(t)}} = \rho g \operatorname{sech}(kh) \tag{1}$$

where k is the radian wave number and h the depth.

In a monochromatic sea ($\eta = a \cos 2\pi ft$) the mean square of the pressure $\overline{p^2}$ and of its time derivative $\overline{\dot{p}^2}$ immediately yield the wave frequency f:

$$\frac{\overline{\dot{p}^2}}{\overline{p^2}} = (2\pi f)^2 \tag{2}$$

and, using the linear theory dispersion relation:

$$k = \frac{(2\pi f)^2}{g} \coth (kh) \tag{3}$$

kh may be determined iteratively or from tables. The amplitude of the surface wave, a, follows from (1).

However, in a natural wind-generated sea, such a simple approach is rendered impossible by the factor sech (kh) in (1). In fact (2) must be rewritten.

$$\frac{\overline{\dot{p}^2}}{\overline{p^2}} = f_p^2 \; G \; \{E_{(f)}, kh\} \tag{4}$$

However, f and k are linked by (3) therefore it is sufficient to know the surface deviation spectrum $E_{(f)}$ in order to correct the measured ratio $\overline{p_t^2} / \overline{p^2}$ for $(2\pi f_p)^2$. Of course, $E_{(f)}$ is unknown and we arrive at an apparent impass. This difficulty may be resolved by making use of the self-similarity of the wind-generated spectrum. From Donelan, Hamilton and Hui (1980) we obtain a parametric description of the deep water spectrum $E'_{(f)}$:

$$E'_{(f)} = \alpha g^2 (2\pi)^{-4} f^{-4} f_p^{-1} \exp\left(-\frac{5}{4}\left(\frac{f_p}{f}\right)^4\right) \gamma^{\exp\left\{-22\left(\frac{f}{f_p} - 1\right)^2\right\}} \tag{5}$$

where $\alpha = 0.006 \, R^{0.55}$

$$\gamma = \begin{cases} 2.2 & ; \quad R < 1 \\ 2.2 + 7.7 \log_{10} R & ; \quad R \geqslant 1 \end{cases}$$

where $R = 2\pi f_p U/g$ is the ratio of wind speed to the theoretical phase velocity of the peak of the spectrum.

Evidently the spectrum $E'_{(f)}$ is completely determined by f_p and U, the average wind speed at 10 metres height. If there is no knowledge of the local wind speed, use may be made of the observation that for fetches greater than a kilometre or so the ratio R generally falls within the range:

$$1 < R < 3$$

Therefore the arithmetic average value of this parameter range $\overline{R} = 2$ will suffice in the absence of wind information.

Note that this parametric description of the spectrum is valid only in deep water, but with beach geometry and angle of wave approach approximately known, the refracted and shoaled shallow water spectrum $E_{(f)}$ may readily be deduced from a given deep water spectrum $E'_{(f)}$.

Because of the similarity of the spectra (5) only two parameters suffice to describe the function G. They are the product of peak wave number and depth $k_p h$ and the ratio R. Thus, (4) may be written:

$$\frac{\overline{p^2}\, f_p^2}{\overline{\dot{p}^2}} = G'(k_p h, R) \tag{6}$$

G' may be determined by numerical application of (5) using shoaling spectrum transformations,(1) and (3) and the fact that

$$\left.\begin{aligned} \overline{\eta^2} &= \int_0^\infty E_{(f)}\, df \\ \overline{\dot{\eta}^2} &= (2\pi)^2 \int_0^\infty f^2 E_{(f)}\, df \end{aligned}\right\} \tag{7}$$

Once G' is known an iterative procedure using (3) and (6) may be applied to establish f_p for any value of R. R and f_p together with beach geometry yield $E_{(f)}$.

Another approach would be to record the time series $p_{(t)}$ for 20 minutes or so, compute the spectrum of pressure fluctuations and finally use (1) and (3) to obtain the spectrum of surface elevation. This approach requires a great deal of analysis time and enormous recording capacity if run say twice a day for 20 minutes. Some pre-selection of data is possible by recording only when $\overline{p^2}$ exceeds a preset threshold, but this would require the design of a control circuit and some accurate clocking to keep track of the data sampled.

3.0 MEAN WATER LEVEL MEASUREMENT

In either of the above methods, the water depth must be accurately known. Again a pressure sensor, suitably averaged, is the most appropriate sensor for the task.

4.0 RECOMMENDATION 1

The wave measurement system which will meet the problem posed by Dr. Sly is outlined in Figure 1.

5.0 COSTS

The recommended system uses a commercial digital integrating recorder. The entire package would be installed underwater and left unattended for as long as a year. While the capital cost of this recorder is appreciable the suggested system would realize significant savings over a system designed around in-house chart recorders. The latter, although inexpensive, would incur other significant costs (a) in the design phase, involving timers, clock codes; (b) in the field operation, involving frequent chart changing, checking of cables; (c) in the analysis, which would have to be done by laborious hand abstraction from charts.

TABLE 1 Cost and Availability of Components of a Wave and Water Level Recorder

Item	Description	Availability	Cost: Material $	Cost: Labour M-Days
* 1	Pressure transducer 0-5 V for equivalent head change of 20 m. Repeatability 2 cm.	In house	0	0
* 2	Circuit to be designed and built in house.	Commercial components	200	10
* 3	Commercial "Sea Data" recorder (analysis system available in house)	12 weeks	8500	0
4	Battery power pack and pressure case	In house	400	10
5	Operational cost, batteries, tape, per year.		200	Site dependent
6	Analysis for M.W.L., significant height and period.	Additional In House Programming	0	5

* These items refer to corresponding numbers on figure 1.

Thus it is clearly possible to satisfy Dr. Sly's requirements with an initial outlay of $9,300 and about 25 man days. The operational costs of $200 a year do not cover installation and maintenance which are extremely site dependent.

APPENDIX

This report was written to address the problem of measuring waves and water levels in the littoral zone. The recommended solution uses a commercial integrating digital recorder with internal clocking. It is worth pointing out that the capital cost of the basic system is increased only marginally by the addition of other recording channels (approximately $600/channel). It would be prudent therefore to purchase the recorder with the number of channels equal to the number of pieces of information one would like to acquire in this manner in the littoral zone. The remaining task would be to find or devise suitable transducers for converting the field variables of interest into a voltage signal.

This appendix addresses the measurements of temperature, drift velocity and sediment transport.

TEMPERATURE MEASUREMENT

Several in-house temperature sensors would be compatible with this system. The effort required to add this parameter is surely outweighed by the usefulness of such temperature data.

DRIFT VELOCITY MEASUREMENT

Attempts to measure longshore and shore-normal drift velocities using mechanical sensors, on the one hand, are usually frustrated by fouling of the moving parts, while, on the other hand, solid state devices are usually not capable of the long term stability required and are also subject to fouling. A sensor using ducted heated thermistors is proposed, which may be able to overcome most fouling problems and which should be stable enough for the job.

The concept outlined below was inspired both by the work of Manuel Pedrosa (personal communication) and the published work of R. K. Steedman of Flinders University, Australia. Pedrosa's instrument uses the cooling of a heated element to sense very low flows and was designed to measure the flow in peat moss. Steedman's instrument is very similar in concept but differs in the choice of heated element and housing configuration from the one outlined below. Steedman's instrument is highly non-linear and therefore not much use in this application where the average drift velocity is to be extracted from a highly oscillatory flow.

The principle of the drift velocity sensor shown in Fig. 2 is simple. The flow from left to right is reduced by the expansion of the housing. The reduced flow v_2 passes over thermistor R_L and out the outlet ports. At the same time, the fluid around R_R remains nearly motionless, so that R_L is cooled more than R_R, thereby producing an imbalance in the bridge e_o. The reverse is true when the flow is from right to left and the bridge imbalance takes on the opposite sign. A change in ambient temperature has no effect on the zero if the thermistors are perfectly matched. There is, however, a small effect on the gain, but this can be determined in calibration and extracted in analysis if the temperature is measured.

Fouling:

Algal growth inside the sensor should not be severe because its normal orientation will be with the long axis horizontal and little sunlight will enter it. However, the outer housing can be constructed of two half shells split along the long axis. This would facilitate construction, maintenance and pre-field painting of the inside of the outer housing with non-reflective anti-fouling paint.

Clogging:

The free passage of suspended sediment through a sensor such as this would eventually lead to partial blockage and calibration changes. To avoid this a system of screens at both entrances would be necessary (see Fig. 2). The first coarse screen would stop large sediment particles and floating matter such as leaves. These would be rejected when the flow changes direction. The second screen would need to be fine enough to reject all particles which would not remain in suspension at typical expected values of v_2. This screen would be very susceptible to calibration changes through algal growth and therefore must be far enough inside the tube to be in virtually total darkness. A small slot at the bottom of the tube just outside each inside screen would prevent a build-up of the trapped sediment.

Since it is clear that any clogging of the screens will cause a reduction in sensitivity, one further simple idea to avoid clogging is worthy of consideration. A cylinder placed normal to the flow is subject to a lateral fluctuating lift force through shedding of eddies from the cylinder. Thus rods attached to the screens as shown in Fig. 2 (vibrating rods) will vibrate at a frequency, proportional to the instantaneous velocity, of about v_o/d_r hertz;

where d_r is the rod diameter. This vibration should have the effect of clearing the screens of sediment particles and other floating matter, since these will only be in motion when there is a current and hence vibration of the screens. It may also inhibit the growth of algae to some extent.

Design Criteria:

The resistance of an element heated by a constant current, I, and cooled by a convection velocity, v_2, is described by the following equation (Hinze, 1959)

$$\frac{I^2 R}{R - R_0} = A + B\sqrt{v_2} \qquad (8)$$

where R is the resistance of the element, R_0 its value at the temperature of the fluid and A and B are dependent on the properties of the fluid and are given in Hinze (1959). For water temperature in the range of 0 to 10^{o}C and overheat of about 20^{o}C, the Prandtl number ($P_r = c_p \mu/k$) is 9.1 and the thermal conductivity k is 0.597 watts $m^{-1}\ {}^{o}C^{-1}$. Thus

$$A = 1.23\ \ell_R\ \beta^{-1}\ R_0^{-1} \qquad \text{amps}^2$$

$$B = 2.22\ \ell_R\ \beta^{-1}\ R_0^{-1}\sqrt{\frac{d_R}{\nu}} \qquad \text{amps}^2\ (\text{m/s})^{-1/2}$$

where ℓ_R is the length of the heated element, d_R its diameter, β its temperature coefficient of resistance (units: ${}^{o}C^{-1}$) and R_0 its resistance at ambient temperature.

From this design information a suitable choice of thermistor and circuit design may be made to yield a suitably sensitive dependence of $e_4(t)$ on v_2.

$$v_2 = \left(\frac{d_1}{d_2}\right)^2 v_1 \qquad (9)$$

The relationship between v_1 and v_0 depends on Reynolds number $v_1 d_1/2\nu$; where is the kinematic viscosity $\doteq$ 0.013 cm^2/sec in water. At low Reynolds number ($R_e < 10^3$) the flow is laminar (Poiseuille flow). Noting that v_1 depends largely on the small tube of length 2L:

$$\left.\begin{aligned} v_1 &= \frac{d_1^2 \, \Delta p}{64 \, \nu \, \rho L} \\ \Delta p &\doteq \frac{\alpha}{2} \, \rho \, (v_0^2 - v_1^2) \end{aligned}\right\} \qquad (10)$$

Δp is the pressure drop across the tube of length 2L; and α is a constant of order 1.

The screens will introduce some pressure drop but the effect can be absorbed into α.

$$v_1 = \frac{\alpha}{128} \; \frac{d_1^2}{\nu L} \; (v_0^2 - v_1^2) \qquad (11)$$

writing $\frac{\alpha}{128} \frac{d_1^2}{\nu L} = C$

$$v_1 = \{ (1 + 4 c^2 v_0^2)^{1/2} - 1 \} / 2c \qquad (12)$$

At Reynolds numbers between 10^3 and 10^4 the flow undergoes transition to turbulence and the dependence of v_1 on v_0 is erratic. Therefore, the sensor must be designed such that $R_e < 10^3$.

Equation (11) applies only if the tube is relatively long. Therefore d_1/L must be $\lesssim$ 0.1. Clearly v_1 is less than v_0 and for proper operation $v_1 < v_0/2$. Therefore the maximum expected value of v_0 is determined from the theoretical bottom velocity caused by the waves neglecting, for the moment, the relatively small average drift velocity.

$$(v_0)_{max} = 2\pi \, f_p \, a \cos \theta / \sinh (kh) \qquad (13)$$

where θ is the angle between the orientation of the sensor and the expected approach direction of the peak waves.

Some standardization would aid design and construction of these sensors. Heated thermistor sensitivity and size suggest that v_2 and d_2 should be about 4 cm/s and 2 cm respectively. Reynolds number considerations restrict d_2/d_1 to be 2 or greater.

Therefore set d_2=2 cm, d_1=1 cm and select L such that, for $(v_0)_{max}$ from (13), $(v_1)_{max} = 1/2 \, (v_0)_{max}$ from (12) provided that $L \gtrsim 10$ cm. The sensor may then be calibrated with various lengths of L appropriate to different applications, and may be constructed so that L can be altered without rebuilding the sensor.

This particular design yields a sensor which is approximately linear in output ($e_4(t) = \text{GAIN X IR}$) with respect to changes in v_0. This may be seen by comparing (8), (9) and (12) and noting that in the bridge arrangement of figure 2 $IR \ \alpha \ \text{sgn}(v_2) \ B \sqrt{|v_2|}$.

Further linearization can easily be included in the bridge amplifier shown in figure 2.

There will be some filtering of frequencies f such that $f\, d_1^2/\nu > 1$ (Schlichting, 1960), and it may be necessary to correct the measured drift velocity for the orbital bottom velocities deduced from the pressure measurements discussed in the main part of this note.

Wave Direction:

The drift velocity sensor may placed so as to measure either longhsore drift currents or shore-normal ones. The signal may also be band pass filtered, squared and integrated as for the pressure signal. The ratio of rms velocities in the wave frequency band (0.05 Hz to 0.5 Hz) from the longshore versus shore-normal sensors yields the tangent of the direction of wave approach $\tan^2\theta$. The sign of θ may be deduced from the sign of the mean product of the longshore wave velocity and the bottom pressure $p_{(t)}$.

SUSPENDED SEDIMENT MEASUREMENT

Figure 3 illustrates an idea for the measurement of suspended sediment transport.

The screens are chosen to bracket the sediment size distribution expected. Diameters d_1 and d_2 are sufficiently large so that the fluid flow is virtually unimpeded in its passage through pipes and screens i.e. $v_0 \doteqdot v_L = -v_R$. Sediment flow is arrested at the fine screen and the solids fall (or are shaken down by the vortex shedding rod) into the sediment trap.

The output of the differential pressure transducer is applied to the digital integrating recorder. The difference of successive readings yields the net sediment transport between readings. The sign of the difference yields the direction of transport. This sensor might appropriately be named a "differential sediment interceptor".

To avoid collecting sediment which is simply oscillated by the waves, the length L of the inlets should be adjusted so that it is larger than the component of the orbital radius in that direction.

$$L > a \cos \theta / \sinh (kh)$$

When L/d_1 is larger than about 5 there may be a tendency for sediment to settle along the bottom of the inlet pipes. Resuspension can be enhanced by judicious placement of vibrating rods or by making the bottom of the tube of flexible material so that it is caused to move by the flow around it.

The direction of drift velocity and that of sediment transport should, of course, agree, but the sensors as discussed do not assume this and therefore are self checking to some degree.

BED LOAD MEASUREMENT

The measurement of bed load is the most difficult of the desirable littoral zone measurements. The problem simply stated is that of measuring the flow velocity of those sediment particles which are transported by rolling, sliding and possibly skipping along the bottom but which generally do not leave the bottom by more than a diameter or so. Clearly, a device is needed which will "float" on this moveable bed and respond in some reproducible way to the motion of the bed.

Let us first consider the simpler problem of measuring the bed load transport beneath a uni-directional fluid flow rather than in the oscillatory flow characteristic of the littoral zone's benthic boundary layer.

Of all the possible ways of measuring wind speed a simple differential drag device known as the "cup anemometer" dominates the operational field by shear weight of numbers. The reasons for the success of the cup anemometer over the past century or so lie in its simplicity, ruggedness and inexpensiveness - the very characteristics that would top anybody's list of criteria for long term littoral zone sampling. Consider therefore the variant of a cup anemometer shown in figure 4.

The heavy base with rigidly attached support rod is implanted in the sediment such that it is beneath the depth of expected erosion and the top of the rod is well above the depth of expected deposition. The differential drag wheels, for ruggedness and simplicity, are fashioned from rectangles approximately 50r long by the expected depth of the bed load movement b. They are separated by about 2b and between them, very close to the top of the lower drag wheel, is the floatation ring. The drag wheels are free to rotate relative to each other and the wheels and floatation ring are free to ride up and down on the support rod, but are constrained to maintain their vertical separation. The materials and sizes are chosen such that the wheels and ring "float" with the lower wheel just buried in the moveable bed. The 'run' of fluid and sediment past the support rod cause the upper and lower drag wheels to rotate independently. The total rotation in a given time is sensed (possibly by capacitance proximity detectors) and converted to a suitable voltage, for averaging by the digital integrating recorder.

In deference to its natural ancestor, the cup anemometer, this device might well be dubbed a "blade sedimometer".

Turning now to the type of flow characteristic of the littoral zone, we see immediately that this device will respond to the average transport speed, $1/T \int |v_T| dt$ rather than the transport velocity component $1/T \int v_\ell \, dt$ of interest. However, the drift velocity sensor yields the net drift and the wave pressure measurements yield information on the wave orbital velocities on the bottom. The bed load transport will have the sign of the net drift and be related to the net drift, the wave orbital velocities, the wave pressure and bed mobility. The information provided by the drift velocity sensor (longshore and shore-normal) and the blade sedimometer together with some clever laboratory experimentation should close the gap between sensed bed load run and bed load transport.

In view of the length of this appendix it would be well to close with a summary table of additional variables which might profitably be sensed and recorded by an automatic instrument for long term littoral zone measurements (Table 2).

TABLE 2 **USEFUL VARIABLES FOR PROBING THE LITTORAL ZONE**

Sensor Number	Sensor	Sensed	Computed	Channel Number
1	Pressure Transducer	Pressure, $p_{(t)}$	$\overline{p_{(t)}} \rightarrow$ M.W.L.	1
1	Pressure Transducer	Pressure, $p_{(t)}$	$\overline{p^2} \rightarrow$ SIG. HT.	2
1	Pressure Transducer	Pressure, $p_{(t)}$	$\overline{\dot{p}^2} \rightarrow$ Period	3
2	Thermistor	Temperature, $T_{(t)}$	$\overline{T}_{(t)}$	4
3	Drift Velocity Sensor	Longshore velocity $v_{x(t)}$	$\overline{v_{x(t)}}$	5
3	Drift Velocity Sensor	Longshore velocity	$\overline{v_x^2}$	6
4	Drift Velocity Sensor	Shore-normal velocity $v_{y(t)}$	$\overline{v_{y(t)}}$	7
4	Drift Velocity Sensor	Shore-normal	$\overline{v_y^2}$	8
1,3	Sensor 1 and Sensor 3	$p_{(t)}$, $v_{x(t)}$	$\overline{p_{(t)} \cdot v_{x(t)}}$	9
5	Differential Sediment Interceptor	Longshore sediment transport V_x	$\overline{V}_x$	10
6	Differential Sediment Interceptor	Shore-normal sediment transport V_y	$\overline{V}_y$	11
7	Blade Sedimometer	Bed load run V_b	$\overline{V}_b$	12
7	Blade Sedimometer	Fluid run above bed V_f	$\overline{V}_f$	13

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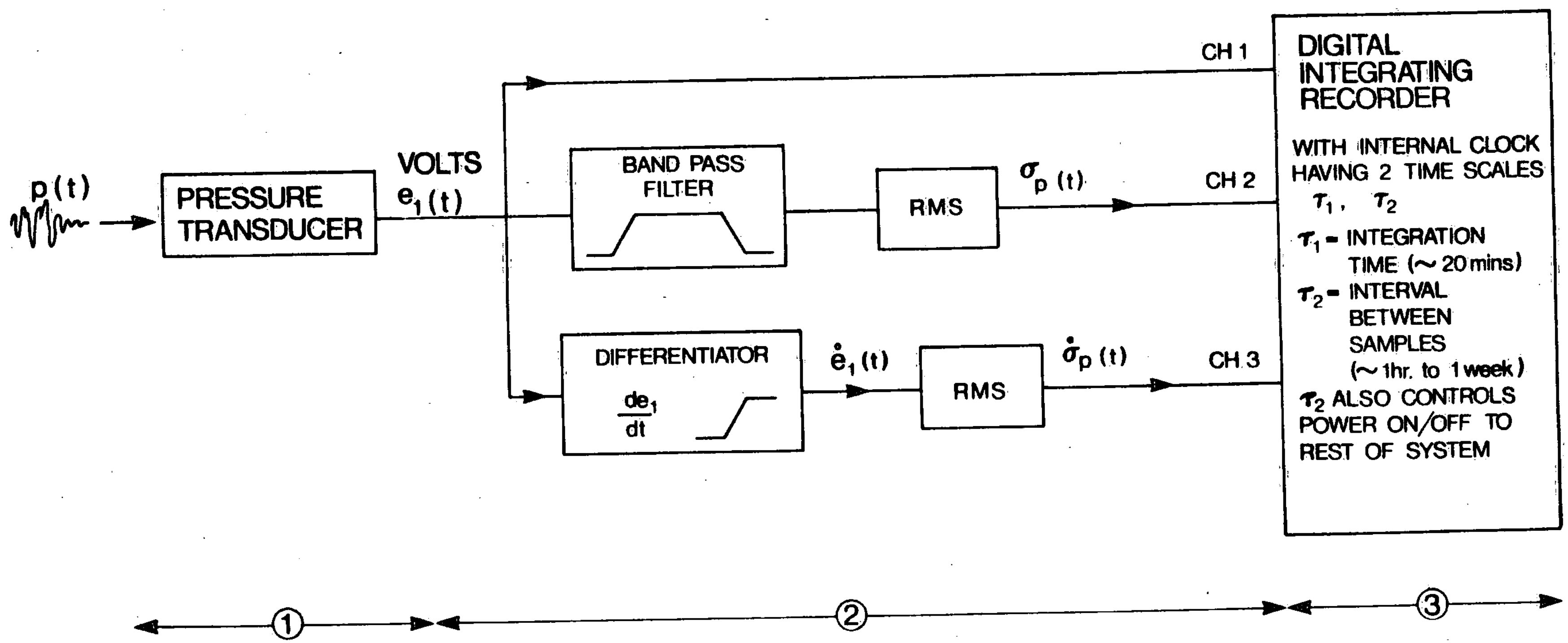
FIGURE CAPTIONS

Fig. 1 Block diagram of an automatic instrument for long-term wave and water level measurements. Chanel 1 (CH 1) yields the mean water level in terms of pressure $\overline{p}$. Channel 2 (CH 2) yields the average root mean square pressure deviation $\sqrt{\overline{p^2}}$. Channel 3 (CH 3) yields the average root mean square of the time derivative of the pressure $\sqrt{\overline{\dot{p}^2}}$.

Fig. 2 Concept of a drift velocity sensor for use in measuring slow drift velocity components in the presence of relatively large wave-produced oscillatory flow.

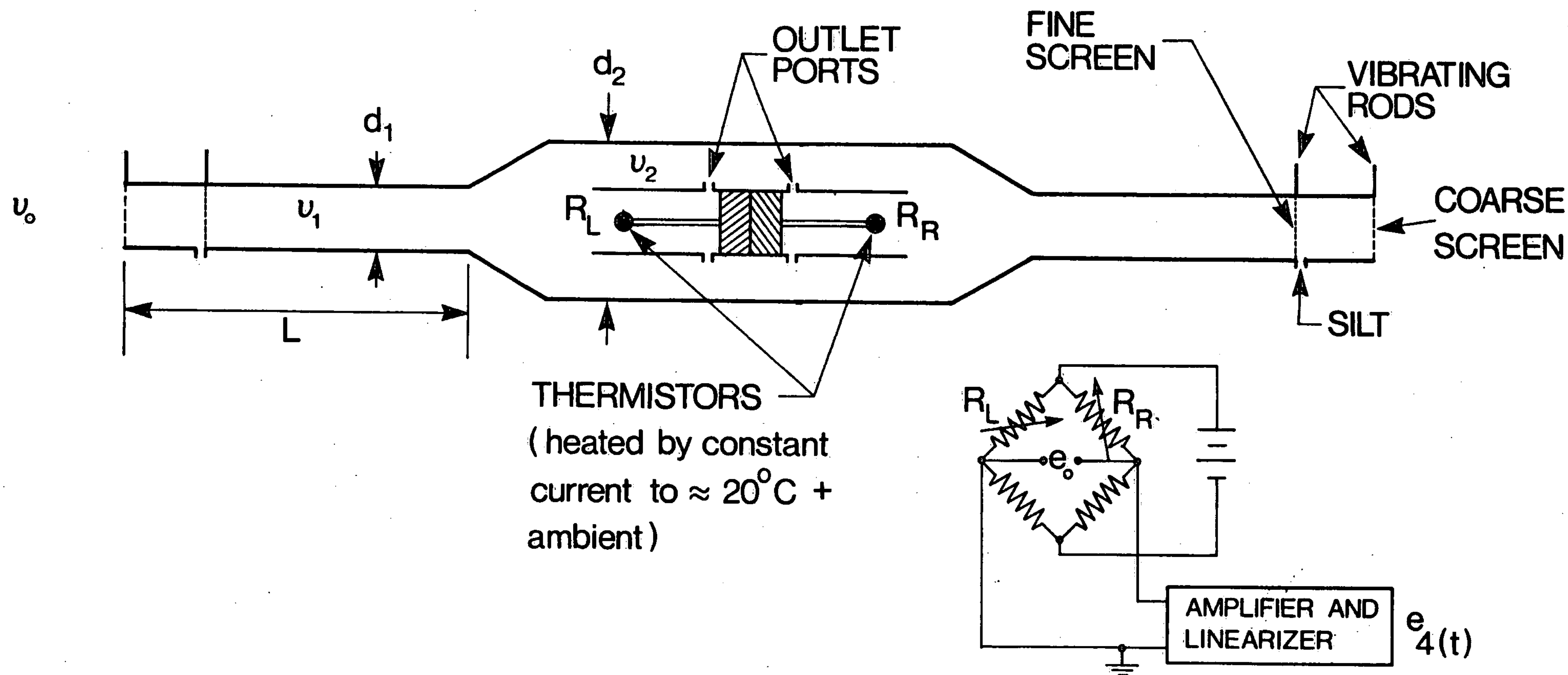
Fig. 3 Concept of a "differential sediment interceptor". This instrument is designed to measure net sediment transport in the presence of large oscillatory transports caused by waves.

Fig. 4 Concept of a "blade sedimometer". This instrument indicates the movement of bed load and the boundary layer flow above the bed, but gives no indication of direction.



p(t)
PRESSURE TRANSDUCER
VOLTS
e1(t)
BAND PASS FILTER
RMS
σp(t)
CH 1
CH 2
DIFFERENTIATOR
de1/dt
ė1(t)
RMS
σ̇p(t)
CH 3
DIGITAL INTEGRATING RECORDER
WITH INTERNAL CLOCK HAVING 2 TIME SCALES
τ1, τ2
τ1 = INTEGRATION TIME (~ 20 mins)
τ2 = INTERVAL BETWEEN SAMPLES (~ 1hr. to 1 week)
τ2 ALSO CONTROLS POWER ON/OFF TO REST OF SYSTEM
1
2
3

FIGURE 1



υ₀
υ1
d1
L
d2
υ2
OUTLET PORTS
R_L
R_R
FINE SCREEN
VIBRATING RODS
COARSE SCREEN
SILT
THERMISTORS
(heated by constant current to ≈ 20°C + ambient)
R_L
R_R
e₀
AMPLIFIER AND LINEARIZER
e4(t)

FIGURE 2

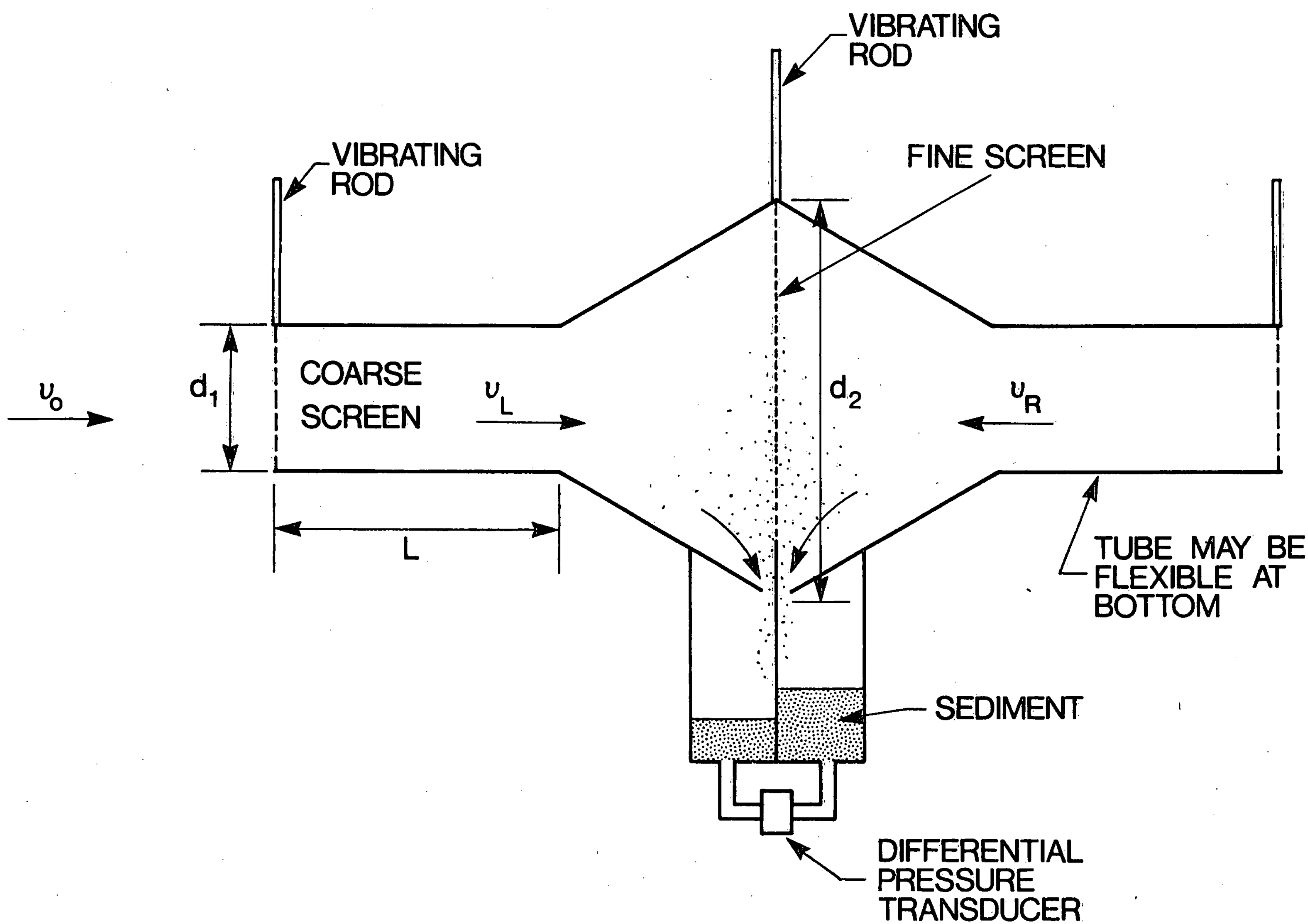

VIBRATING ROD
VIBRATING ROD
FINE SCREEN
COARSE SCREEN
υ_o
d_1
υ_L
d_2
υ_R
L
TUBE MAY BE FLEXIBLE AT BOTTOM
SEDIMENT
DIFFERENTIAL PRESSURE TRANSDUCER

FIGURE 3

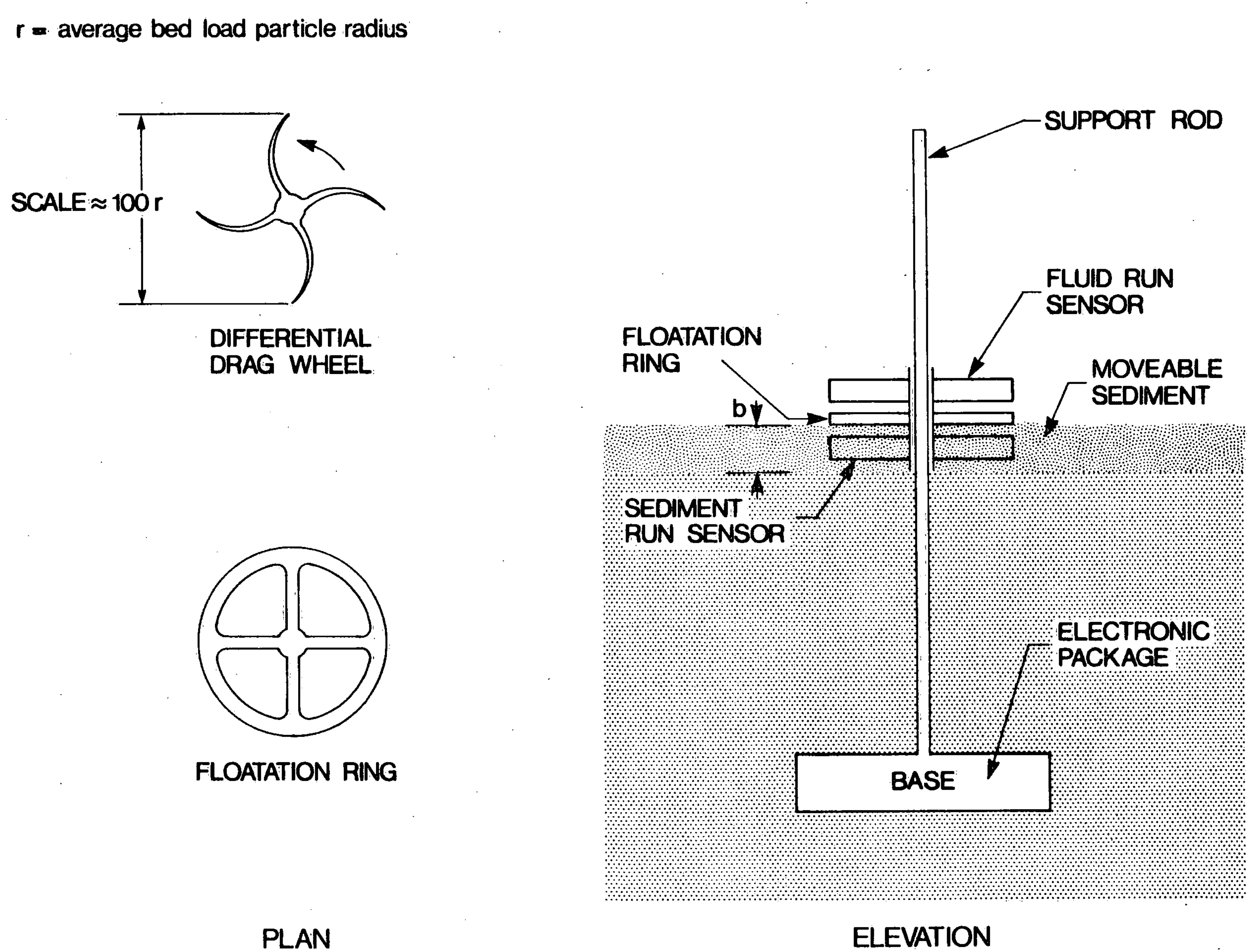


FIGURE 4

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National Water Research Institute
~~Canada Centre for Inland Waters~~. Hydraulic Research Division. Technical Note.