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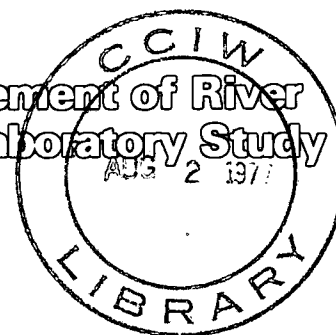and Environment
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Tracer Measurement of River Evaporation: Laboratory Study

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Y. L. Lau

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Abstract

Experiments were performed in a small wind tunnel in which the wind blew over a basin of water containing tritium. Evaporation rates for water vapour and tritium were measured. The results show that the wind function for water evaporation and that for tritium evaporation were affected to about the same degree by turbulence in the air. However, turbulence in the water greatly increased the evaporation rate of the tritium but not that of the water. Application of the laboratory measurements to the development of a method for measuring river evaporation is discussed.

Résumé

On a effectué des expériences dans une soufflerie où le vent soufflait sur un bassin d'eau renfermant du tritium, afin de mesurer les vitesses d'évaporation de la vapeur d'eau et du tritium. Les résultats indiquent que la turbulence de l'air a sensiblement le même effet sur l'évaporation de l'eau et sur celle du tritium. Par contre, la turbulence de l'eau augmente considérablement la vitesse d'évaporation du tritium, mais non celle de l'eau. Le présent rapport a pour but d'étudier l'application des expériences de laboratoire à l'élaboration d'une méthode permettant de mesurer l'évaporation dans les cours d'eau.

List of Symbols

b	rate of change of water depth with time (mm/min)
C	concentration of tritium in the water
C_o	initial tritium concentration
D	molecular diffusivity of water vapour in the air (cm^2/s)
E_t	rate of evaporation of tritium per unit area (g/cm^2/s)
E_w	rate of evaporation of water per unit area (g/cm^2/s)
h	depth of water in the basin (mm)
h_o	initial depth of water (mm)
K	von Karman constant
n	exponent in the concentration versus depth relationship
P_a	partial pressure of water vapour in the air (mm Hg)
P_w	saturation water vapour pressure at the temperature of the water surface (mm Hg)
q_a	specific humidity in the air (grams of water vapour/gram of mixture)
q_w	specific humidity at the air-water interface (grams of water vapour/ gram of mixture)
r	ratio of ψ_w to ψ_t
St_t	Stanton number for tritium flux $= E_t/\rho_w UC$
St_w	Stanton number for water vapour flux $= E_w/\rho_a U(q_w-q_a)$
t	time (min)
U	wind speed (m/s)
U_*	shear velocity (cm/s)
Z	height above water surface (cm)
Z_o	roughness length (cm)
ψ_t	wind function for tritium transfer (mm/min)
ψ_w	wind function for water vapour transfer (mm/min/mm Hg)
ρ_a	air density (g/cm^3)
ρ_w	water density (g/cm^3)
ν	kinematic viscosity of air (cm^2/s)

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INTRODUCTION

Because of the increasing demand for energy, many more rivers and streams are likely to have their thermal regimes affected by waste heat discharges. From a management standpoint, it is important not only to know the natural temperature variations in a river but also to have the ability to predict temperature variations caused by changes in the use of a stream. Numerical models are being developed for this purpose. However, they can give reliable results only if input parameters such as the heat flux terms at the air-water interface can be accurately described.

The various heat transfer processes between water and atmosphere have been described by many authors, e.g. Anderson (1954) and Parker and Krenkel (1969). The most important of these are the net incoming radiation, long-wave back radiation emitted by the water surface, evaporation and heat convection from the water. The net incoming radiation can be measured directly and the back radiation can be computed using the Stefan-Boltzman law. The convection term is usually calculated from the evaporation term using the Bowen ratio concept of identical diffusivities for heat and mass and is usually relatively small. The evaporation heat flux, which can often be as much as 50 per cent of the total heat flux, is the most difficult term to evaluate. Evaporation equations which have been determined from measurements in lakes or reservoirs cannot be applied directly to river flow (Jobson, 1975). The need for an evaporation equation for rivers has been pointed out by Jobson and Yotsukura (1973). However, there is as yet no direct method of measuring the evaporation from river flow except for the eddy correlation technique, which measures the velocity and humidity fluctuations at a single point.

This report describes a series of experiments in which the simultaneous transfer of water vapour and a radioactive tracer into an air flow was investigated. The objective of these experiments is to develop a method for measuring evaporation in river flow by first establishing a relationship between the evaporation rate constants for the two species in the laboratory. The experimental results and the feasibility of this method are discussed.

BACKGROUND

At the air-water interface, water molecules are continuously evaporating and condensing, and what is usually referred to as the rate of evaporation is actually the net of

the evaporation and condensation which takes place. This overall evaporation rate is depen-
dent on the difference between the partial pressure of water vapour in the air and the
partial pressure at the water surface. This vapour pressure difference is more or less the
driving force for evaporation. As evaporation proceeds, the rate at which water vapour can
leave the surface is governed by the rate at which it can be transported upwards out of the
surface layer. If the air above the water is stagnant, the upward transfer of vapour will
depend on molecular diffusion and will be very slow. If, however, there is considerable
turbulence in the air which can rapidly transport any evaporated water out of the surface
region, evaporation will take place at a much faster rate. Therefore, for a given vapour
pressure difference the evaporation rate depends on the conditions of turbulence in the air.
The rate of evaporation is usually calculated from the following equation

$$E_w = \psi_w \, \rho_w \, (P_w - P_a) \tag{1}$$

where E_w = rate of evaporation per unit area

ρ_w = density of water

P_w = saturation water vapour pressure at the temperature of the water surface

P_a = partial pressure of water vapour in the air

ψ_w = the rate constant for evaporation, usually called the Dalton wind function
or the profile coefficient

The wind function ψ_w is obviously not a constant but depends on wind speed, sur-
face roughness and other parameters which affect turbulence conditions in the air.

Equation (1) can be derived by integrating the equations of mass and momentum
transport with respect to the vertical direction. For the atmospheric boundary layer over
a water surface, it can be shown that ψ_w is a function of the turbulent diffusivity and
varies with height. The value of P_a also varies with height, so that in the so-called
"constant flux layer" close to the surface the evaporation rate is constant with height.

The evaporation of a tracer gas which is dissolved in the water follows very much
the same process as evaporation of water vapour. The transport at the interface is again
dependent upon the difference in partial pressure of that particular gas in air and in
water, and the net rate of transport of the tracer out of the water is governed by the
turbulent conditions in the air in the same manner as the evaporation of water. Therefore,
in an experiment in which water vapour and a tracer gas are transported simultaneously out
of the water it should be possible to measure and compare the wind function ψ for both
water and tracer. The ratio between the two ought to be independent of the wind conditions
because the same turbulence conditions prevail for both transports. If a consistent rela-
tionship can be established in the laboratory under different conditions of wind velocity,

turbulence in the water, etc., this relationship should be valid for field conditions as well. It may then be possible to apply this relationship to field measurements of tracer transport to obtain the rate of evaporation of water.

Experiments on isotope evaporation have been conducted previously, but they were aimed at measuring the loss of the isotope (Horton *et al.*, 1971; Prantl, 1974) or comparing different theoretical equations (Merlivat and Coantic, 1975). In this study a series of experiments were performed in which the evaporation of water vapour and tritium gas took place simultaneously and the main objective was to find a relationship between the values of ψ for water and tritium under different conditions.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were performed in a small wind tunnel 125 cm long with a cross section of 15 cm x 30.5 cm. The bottom of the tunnel at the test section was cut away so that a basin 30 cm x 30 cm x 16.5 cm deep could be fitted directly underneath. The basin was filled with water so that the wind blew right over the water surface. The wind tunnel and the basin were made of plexiglass. A schematic sketch of the apparatus is given in Figure 1.
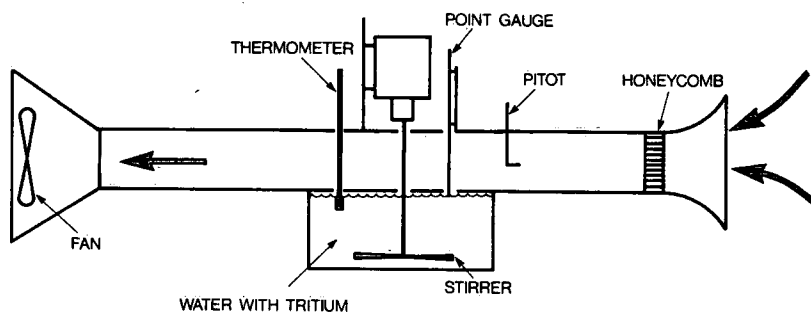

Figure 1. Schematic sketch of apparatus.

Air is drawn in by the fan through a bell-mouth entrance and a bank of flow straighteners, flows over the basin of water and exhausts out of the room. The free stream air velocity was measured by means of a Pitot tube and a differential manometer. The air temperature and humidity were recorded by a hygrothermograph. Wet and dry bulb temperatures were also measured using a sling psychrometer. The water temperature was measured by means of a thermometer readable to 0.1° C. Water level in the basin was measured by means of a point gauge with a vernier readable to 0.1 mm. The fan was driven by a motor with a variable speed drive so that the air velocity could be varied.

Before the start of a run the water level was checked and enough water was added to bring the level to the top of the basin. Usually the fan had already been running at the desired speed overnight so that steady-state conditions had more or less been achieved.

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Therefore, the make-up water was always mixed to the temperature of that in the basin before being added.

Tritium in the form of tritiated water was then added and mixed into the water. At the beginning of a test run the water level was read and a 6-ml water sample was pipetted from the basin and prepared for scintillation counting. The initial water depth and tritium concentration were then known. The water temperature and wet and dry bulb temperatures were also taken. All readings were repeated every 30 min. or so and the time elapsed was recorded. A test run usually lasted for about 8 hr. At the end of a run the wind speed was adjusted for the next run, and the fan was left to run overnight to re-establish steady-state conditions.

Approximately 50 test runs were made, with wind speeds varying between two and seven metres per second. These wind velocities in the tunnel did not cause any significant wave action in the basin nor was there spray created at any time. A number of runs were also made in which turbulence was created in the water by means of a propeller-shaped stirrer, which was being turned at about 40 rpm.

ANALYSIS OF LABORATORY MODEL

In the laboratory experiments a stream of air with a boundary layer type velocity profile but uniform temperature and humidity flows over a body of water which is at another temperature, as shown in Figure 2. The water contains tritium whose concentration in the water is equal to C and in the air is practically zero. The fetch is very short so that there is very little opportunity for the buildup of a water vapour or tritium boundary layer. As the evaporation of water and tritium proceeds, the water level drops and the
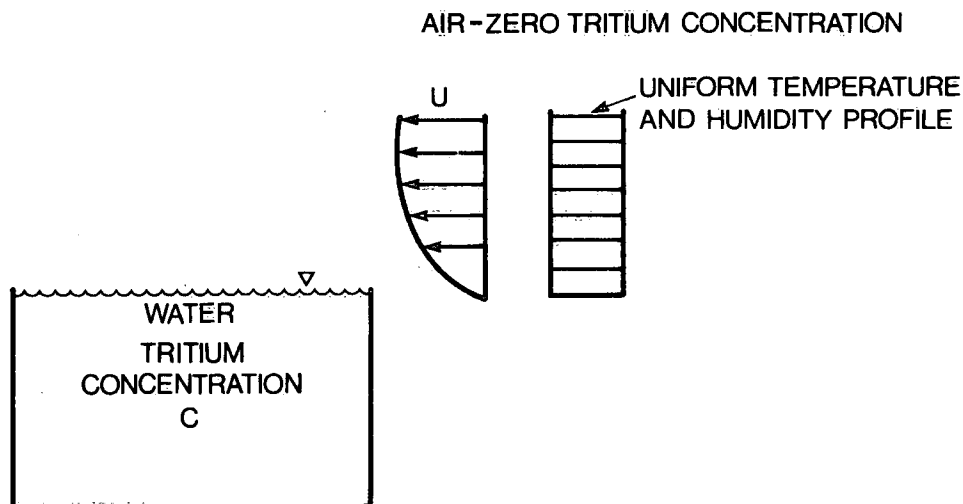

Figure 2. Conditions prevailing in laboratory experiments.

tritium concentration in the water may increase or decrease according to the relative rates of evaporation of the two species. The water depth and tritium concentration can be described by the following equations. For the water the evaporation rate is simply the rate of decrease of mass of water in the basin:

$$E_w = - \frac{d}{dt} \rho_w h \qquad (2)$$

where h = depth of water in the basin

t = time

Equating this rate with the expression for E_w in equation (1) gives

$$- \frac{d}{dt}(\rho_w h) = \psi_w \, \rho_w \, (P_w - P_a) \qquad (3)$$

A similar equation can be written for the tritium, i.e.

$$E_t = - \frac{d}{dt}(\rho_w Ch) = \rho_w \, \psi_t \, C \qquad (4)$$

where E_t = rate of tritium evaporation per unit area

C = tritium concentration in the water

ψ_t = wind function or profile coefficient for tritium

The solution for the water depth h can be obtained by integrating equation (3), resulting in the following expression

$$h = h_0 - \psi_w \, (P_w - P_a) \, t = h_0 - bt \qquad (5)$$

where h_0 = depth of water at time $t = 0$,

and $b = \psi_w \, (P_w - P_a)$ is a constant for a particular run.

Equation (5) shows that the depth of water in the basin should decrease linearly with time. The slope of the h versus t plot is equal to b. From this value, ψ_w for that particular run can be calculated.

Substituting the expression for h from equation (5) into equation (4) and re-arranging, the equation for C becomes

$$\frac{dC}{dt} + \frac{(\psi_t - b)}{h_0 - bt} \, C = 0 \qquad (6)$$

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The solution to equation (6) is

$$\frac{C}{C_0} = (1 - \frac{b}{h_0} t)^{\frac{(\psi_t - 1)}{b}}$$

i.e.

$$\frac{C}{C_0} = (\frac{h}{h_0})^{\frac{(\psi_t - 1)}{b}}$$

$$= (\frac{h}{h_0})^n \tag{7}$$

where C_0 = tritium concentration at time $t = 0$

and $n = \frac{\psi_t - 1}{b}$ is a constant for a particular test.

The exponent n and thus the value of ψ_t can be obtained from a plot of C/C_0 versus h/h_0. The ratio between ψ_w and ψ_t which is valid for the turbulence conditions of that particular run is then established. Variations of the experimental conditions, such as air velocity and mixing conditions in the basin, would allow us to investigate how this ratio is affected.

It should be noted that during each run the water evaporation rate is constant throughout, but the tritium evaporation rate changes as the concentration varies. It is not the actual evaporation rates which are being compared but rather the rate constants ψ_w and ψ_t, which are both governed by the turbulence conditions.

RESULTS AND DISCUSSION

Figure 3 shows a typical plot of water depth h and tritium concentration in counts per minute versus time t for one of the runs. The values for h have been corrected to account for the volumes of samples withdrawn for tritium counting. In general the water depth varied linearly with time for all the runs, as indicated by equation (5), and the slope b and wind function ψ_w could be obtained accurately without using any curve-fitting procedure. A plot of ψ_w versus wind velocity U is shown in Figure 4. As expected, the value of ψ_w increases with U. The rate of increase appears to be linear. Jobson (1975) computed ψ_w for a canal 26 km long from a heat balance study and also found a linear increase with velocity. Slight scatter in the data might have been caused by variations in the vapour pressure difference $(P_w - P_a)$. The room temperature was controlled by an air-conditioning unit, which was able to maintain the air temperature constant with fluctuations of about one or two degrees Celsius. The values of $(P_w - P_a)$ fluctuated about the mean value by about 5%.
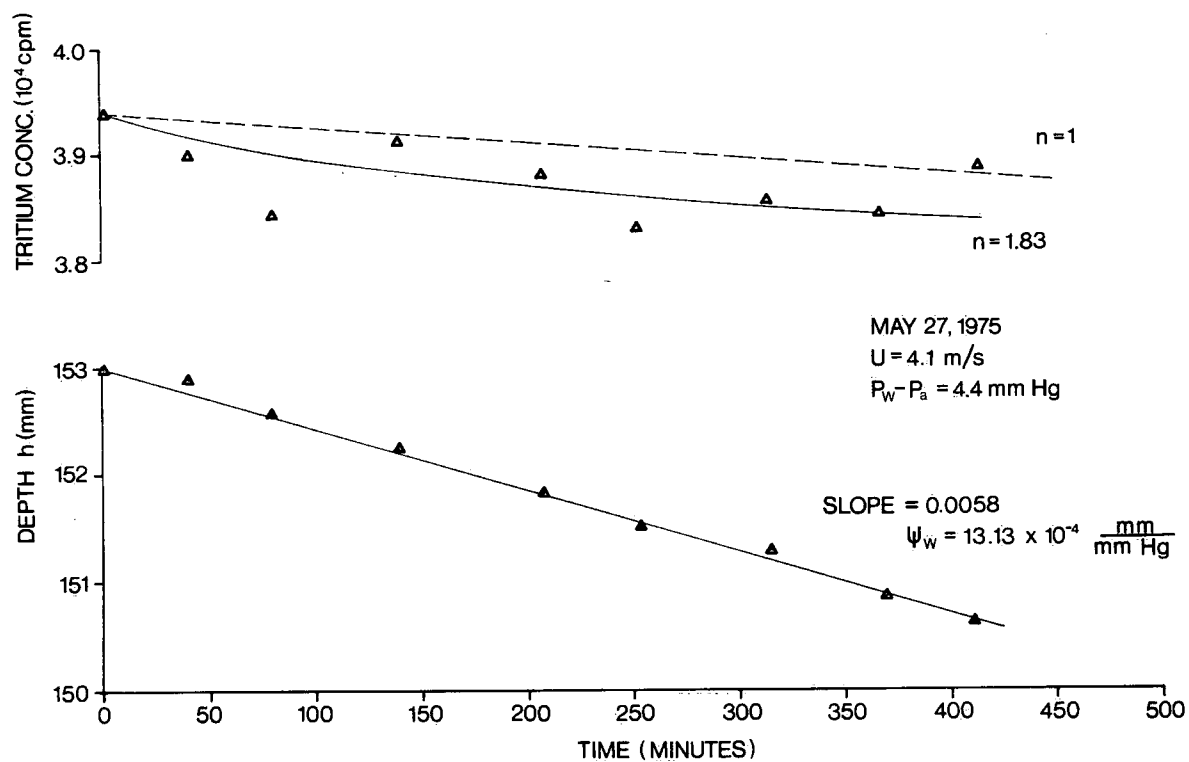
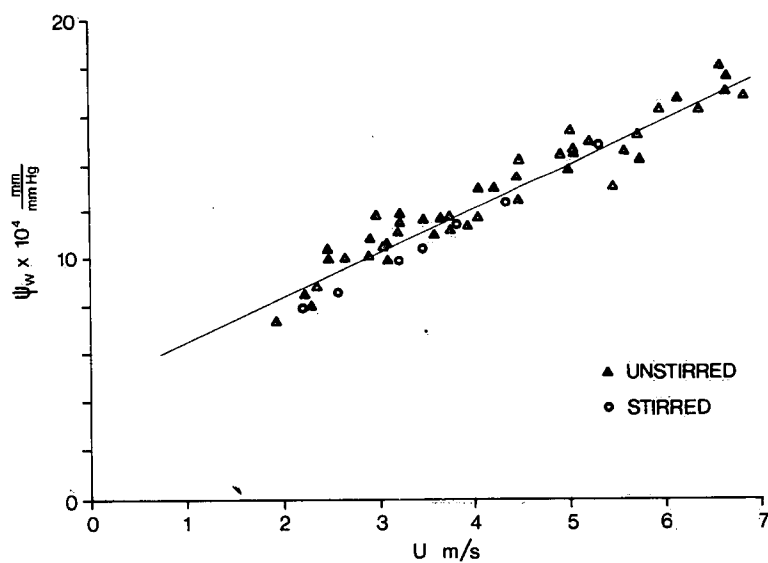Figure 3.   Change of tritium concentration and water depth with time.

Figure 4.   Wind function for water vapour versus
wind velocity.

Table 1. Summary of Experimental and Calculated Data

U (m/s)	C_o (cpm)	h_o (mm)	$P_w - P_a$ (mm Hg)	ψ_w (mm/s/mmHg)	ψ_t (mm/s)	ψ_t/ψ_w	$q_w - q_a$	St_w	St_t	St_t/St_w
3.23	71	147.5	6.35	18.50×10^6	0.235×10^3	12.70	4.93×10^3	6.15×10^3	7.30×10^8	1.19×10^5
3.26	330	150.2	6.10	19.95 "	0.243 "	12.18	4.81 "	6.46 "	7.46 "	1.15 "
4.07	517	149.4	6.30	19.73 "	0.248 "	12.56	5.00 "	5.08 "	6.02 "	1.18 "
3.78	448	147.8	5.05	18.82 "	0.259 "	13.76	4.09 "	5.11 "	6.86 "	1.34 "
5.50	536	145.0	5.65	22.83 "	0.323 "	14.15	4.48 "	4.33 "	5.88 "	1.36 "
6.00	398	150.8	5.25	26.98 "	0.397 "	14.71	4.23 "	4.64 "	6.61 "	1.18 "
3.50	334	152.6	6.15	19.42 "	0.205 "	10.56	4.94 "	5.74 "	5.86 "	1.02 "
2.68	298	152.8	7.00	16.77 "	0.117 "	6.97	5.52 "	6.56 "	4.35 "	0.66 "
5.01	262	156.8	6.30	23.07 "	0.153 "	6.63	5.03 "	4.78 "	3.06 "	0.64 "
4.50	240	150.4	7.30	20.70 "	0.247 "	11.92	5.66 "	4.93 "	5.48 "	1.11 "
4.95	66.1×10^3	150.7	6.30	24.25 "	0.270 "	11.13	4.93 "	5.22 "	5.45 "	1.04 "
5.27	60.6 "	153.2	7.00	25.00 "	0.350 "	14.00	5.50 "	5.02 "	6.64 "	1.32 "
3.73	53.7 "	149.4	7.30	19.63 "	0.287 "	14.60	5.71 "	5.57 "	7.68 "	1.38 "
6.40	42.1 "	150.6	6.60	27.02 "	0.357 "	13.20	5.23 "	4.41 "	5.57 "	1.26 "
6.20	31.4 "	151.3	6.40	27.98 "	0.357 "	12.75	4.99 "	4.76 "	5.75 "	1.21 "
6.71	24.0 "	150.4	6.30	29.53 "	0.372 "	12.58	4.97 "	4.62 "	5.54 "	1.20 "
6.65	20.0 "	147.1	4.00	30.28 "	0.243 "	8.03	3.27 "	4.11 "	3.66 "	0.89 "
6.89	17.2 "	154.0	6.70	27.97 "	0.293 "	13.39	5.26 "	4.28 "	5.42 "	1.27 "
5.76	14.6 "	149.5	5.90	25.28 "	0.298 "	11.79	4.63 "	4.63 "	5.18 "	1.12 "
5.61	12.8 "	151.3	5.75	24.42 "	0.281 "	11.49	4.58 "	4.53 "	5.00 "	1.10 "

U (m/s)	C_o (cpm)	h_o (mm)	$P_w - P_a$ (mm Hg)	ψ_w (mm/s/mmHg)	ψ_t (mm/s)	ψ_t/ψ_w	$q_w - q_a$	St_w	St_t	St_t/St_w
5.08	8.64×10^3	152.3	7.00	25.80×10^6	0.328×10^3	12.75	5.69×10^3	5.17×10^3	6.46×10^8	1.25×10^5
5.08	7.13 "	151.9	5.80	24.44 "	0.346 "	14.18	4.72 "	4.90 "	6.82 "	1.39 "
4.52	6.04 "	152.2	5.60	23.81 "	0.231 "	9.685	4.55 "	5.37 "	5.10 "	1.05 "
4.24	5.12 "	149.9	6.40	21.93 "	0.267 "	12.160	5.17 "	5.33 "	6.29 "	1.18 "
3.62	3.94 "	150.4	5.90	18.50 "	0.218 "	11.76	4.72 "	5.37 "	6.02 "	1.12 "
3.26	3.68 "	151.2	5.25	19.68 "	0.207 "	10.50	4.23 "	6.25 "	6.34 "	1.01 "
3.70	5.49×10^4	148.5	3.70	19.40 "	0.142 "	7.31	3.00 "	5.39 "	3.83 "	0.71 "
4.10	3.94 "	153.0	4.40	21.88 "	0.273 "	12.50	3.59 "	5.49 "	6.67 "	1.21 "
4.24	3.36 "	150.6	4.50	21.60 "	0.194 "	8.99	3.63 "	5.23 "	4.58 "	0.87 "
5.08	2.90 "	150.4	3.85	24.13 "	0.260 "	10.76	3.15 "	4.87 "	5.12 "	1.05 "
2.31	2.18 "	150.4	5.10	13.32 "	0.135 "	10.20	4.14 "	5.92 "	5.88 "	0.99 "
2.26	1.89 "	149.8	5.10	14.37 "	0.147 "	10.21	4.19 "	6.49 "	6.49 "	1.00 "
2.48	1.75 "	151.1	5.75	17.68 "	0.203 "	11.50	4.75 "	7.24 "	8.19 "	1.13 "
2.56	1.56 "	150.1	4.70	16.66 "	0.155 "	9.34	3.89 "	6.53 "	6.08 "	0.93 "
2.02	1.39 "	149.1	5.30	12.10 "	0.128 "	10.60	4.42 "	6.03 "	6.35 "	1.05 "
* 3.50	4.70 "	149.5	4.40	17.30 "	0.333 "	19.29	3.63 "	5.06 "	9.52 "	1.88 "
* 5.35	4.29 "	147.2	4.35	24.63 "	0.547 "	22.21	3.52 "	4.74 "	10.22 "	2.15 "
* 4.39	3.49 "	150.2	3.40	20.58 "	0.521 "	25.32	2.79 "	4.79 "	11.87 "	2.48 "
* 3.86	2.91 "	149.9	3.80	18.97 "	0.327 "	17.27	3.13 "	5.00 "	8.48 "	1.69 "
* 3.23	2.48 "	149.4	4.75	16.48 "	0.325 "	19.71	3.87 "	5.29 "	10.06 "	1.90 "
* 2.31	2.13 "	149.1	4.65	13.40 "	0.328 "	24.48	3.76 "	5.95 "	14.21 "	2.39 "

* Denotes runs in which the water was stirred during the experiment.

The ψ_w values for those runs in which the water was kept stirred appears to be slightly lower than the others. Those runs were all started at slightly lower initial water levels than the regular runs to avoid any spilling which might result from stirring. Therefore, the distance between the floor of the wind tunnel and the surface of the water was larger, and the effective air velocity over the water became slightly lower. This effect is significant and was demonstrated by the results of a few runs in which the evaporation experiment was run at the same air velocity for two or three consecutive days without adding any make-up water. In every case the value of ψ_w was lower for the second day and was lowest for the third day. For cases in which the water depth decreased by 1.5 to 2.0 cm, the decrease in ψ_w was up to 24%. It appears, however, that the 3- or 4-mm decrease in depth which occurred during the course of a run had no noticeable effect on the value of ψ_w.

Data for all runs are tabulated in Table 1.

Obtaining the value of ψ_t turned out to be less straightforward than planned. Equation (7) shows that the slope of a ln-ln plot of $\frac{C}{C_o}$ versus $\frac{h}{h_o}$ is equal to n, from which ψ_t can be calculated. However, the changes in $\frac{C}{C_o}$ and $\frac{h}{h_o}$ both turned out to be very small and it was practically impossible to plot these values on a ln-ln plot. It was decided, therefore, to plot the values of C versus time and then choose a value of n which gives a curve best fitting the data points.

Differentiating equation (7), one obtains

$$\frac{dC}{dt} = -(\frac{bC_o}{h_o}) \, n \, (1 - \frac{b}{h_o} t)^{n-1} \tag{8}$$

From equation (8) one can deduce the shape of the C versus t curve for given values of n. This is shown in Figure 5. The linear slope for the case of n = 1 is equal to $-\frac{bC_o}{h_o}$. Therefore, after plotting the C versus t data for a particular run, the line for the case n = 1 was drawn in, and by comparing this with the data, one could judge within what range the value of n ought to be. Values of n for that range were then tried and the one best fitting the data was chosen. A sample of this plot is shown in Figure 3. From the value of n and the value for b obtained from the h versus t plot, the value of ψ_t could be calculated. Figure 6 shows a plot of ψ_t versus wind speed U for the various runs. There is considerable difference between the stirred and unstirred cases. For the unstirred case the value of ψ_t increases more or less linearly with U, although there is considerable scatter. For the stirred case the data points also indicate an increase with velocity, but the values of ψ_t are much larger than the unstirred case for the same velocities. On the average, ψ_t values increased by about 70% when the water was stirred.

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Thus it appears that, other conditions being constant, turbulence in the water does not affect the water evaporation rate but significantly affects the tritium evaporation rate. This is not entirely unexpected, since water molecules are always present at the interface regardless of turbulence but the supply of tritium to the surface from within the water is affected by turbulence in the water. This also shows that certain schemes such as the use of evaporation pans containing radioactive tracers for measuring evaporation are not feasible because the turbulence in the water is different.

The scatter in the values of ψ_t is due largely to the uncertainties in the value of n. In some instances the value of n can be changed 20% to 30% without significantly affecting the fit to the data, however, with the available data, it is felt that the method used to obtain n was the most reliable. Fluctuations in the readings from the scintillation counter also contributed to the scatter. The tritium counts for any one sample varied from day to day and judgment had to be used to select a series of tritium count values for analysis.
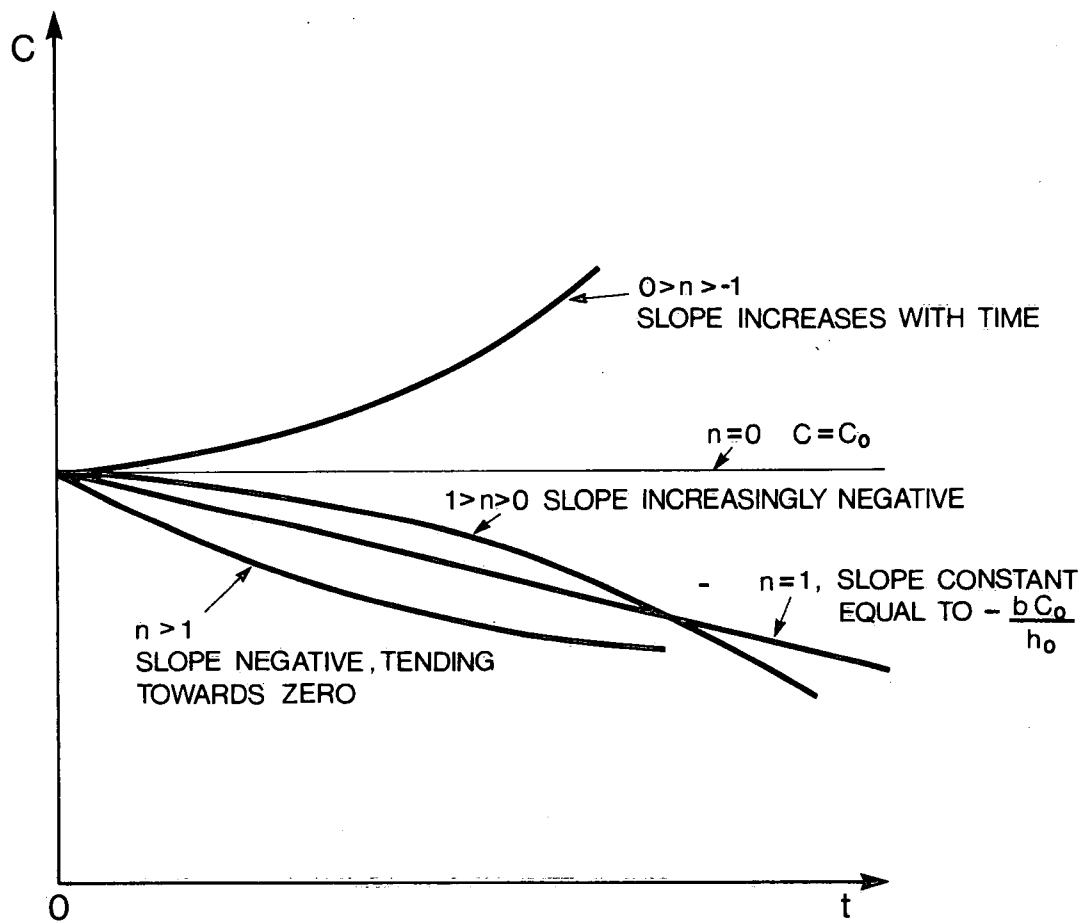

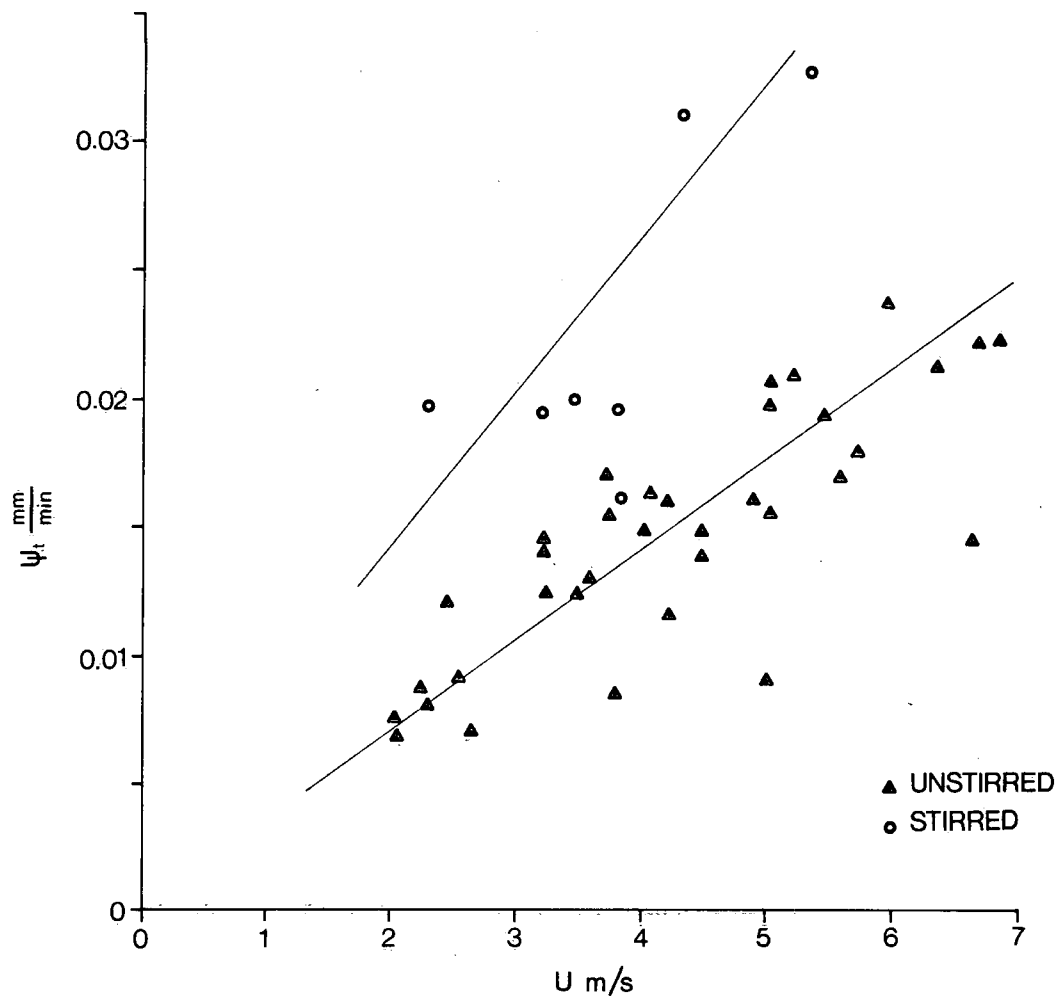Figure 5. Shapes of the concentration versus time curve for different ranges of values for n.

Figure 6. Variation of ψ_t with wind velocity.

It was already mentioned that the important factor in these experiments is not the absolute value of the wind function but the comparison of the values of ψ for water vapour and tritium. The ratio ψ_t/ψ_w was calculated for each run and is plotted against U in Figure 7. It can be seen that ψ_t/ψ_w is more or less constant and independent of velocity for the unstirred case. This indicates that turbulence in the air flow affects ψ_w and ψ_t to the same extent, which is reasonable because both water vapour and tritium were always subjected to the same degree of turbulence. The values of ψ_t/ψ_w for the stirred cases are much higher because of the increased ψ_t with stirring.

In heat and mass transfer literature, the Stanton number, which is a normalized heat or mass flux, is frequently used as an indication of the transfer. As a comparison, the Stanton numbers for the water vapour and tritium fluxes are computed and shown in

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Figures 8 and 9. The Stanton numbers are defined as follows:

$$St_w = \frac{E_w}{\rho_a U (q_w - q_a)} \tag{9}$$

$$St_t = \frac{E_t}{\rho_w UC} \tag{10}$$

where St_w = Stanton number for water vapour flux

ρ_a = air density

q_w = specific humidity at air-water interface

q_a = specific humidity in the air stream
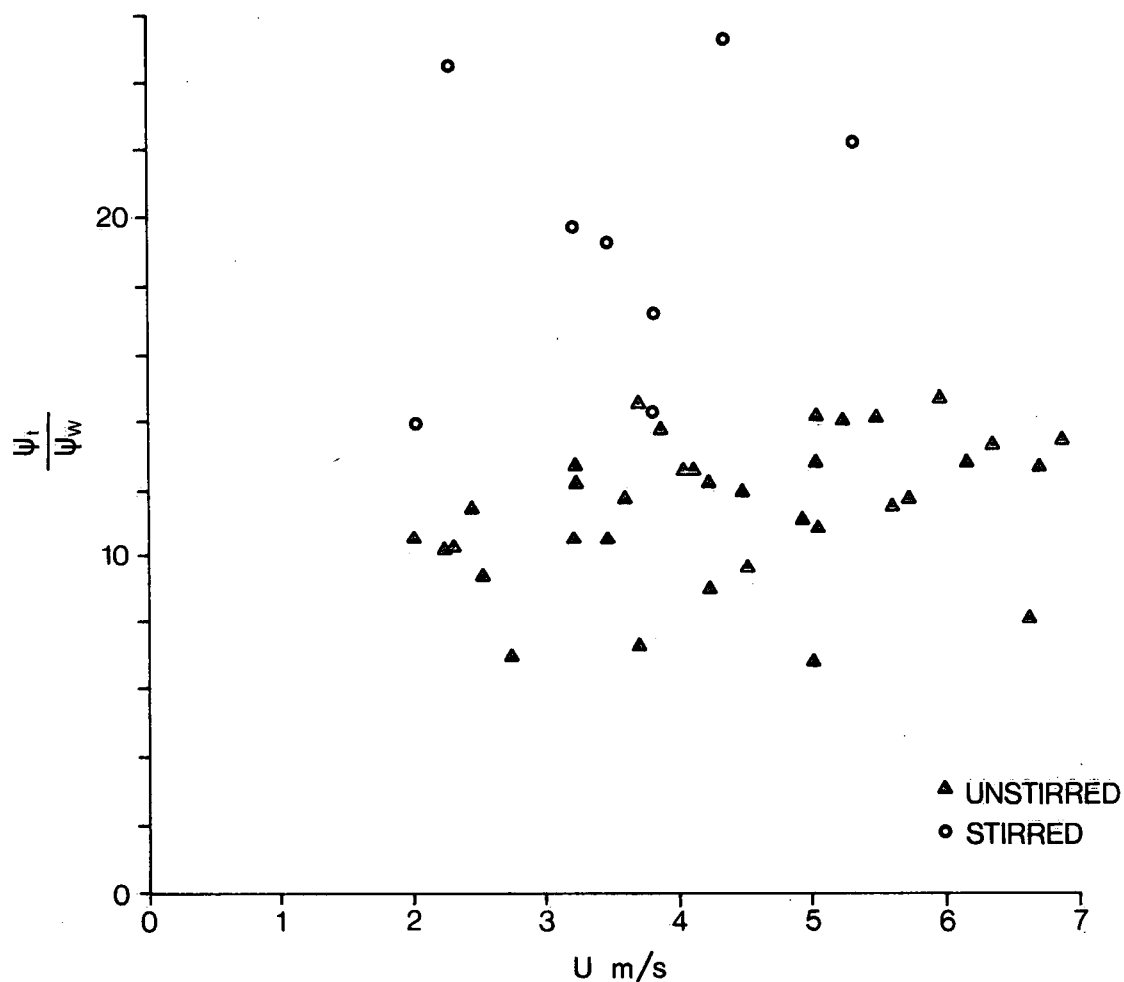
St_t = Stanton number for tritium flux

Figure 7. Variation of ψ_t/ψ_w with wind velocity.

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Figure 8 shows that the Stanton number for water vapour flux decreases with increasing velocity. The average value for St_w is about 5×10^{-3}, which is comparable to those measured in a large wind-wave tunnel (Mangarella et al., 1971) as well as those from field experiments (Monin 1970). Values of St_w for the stirred runs are slightly lower but still within the scatter of the data.

The Stanton number for tritium flux is plotted against wind velocity in Figure 9. The value of St_t also decreases with wind velocity, but the scatter is too large to determine whether the rate of decrease is the same as that for St_w. As expected, the Stanton number for tritium flux is much larger for those runs in which the water was stirred. The numerical values for St_t are much smaller than St_w. The reason is that only tritium concentration in the water was measured and so C and ρ_w were used in the definition of St_t in equation (10). The Stanton number for tritium flux would be much larger if it were calculated based on tritium concentrations in the air at the air-water interface.
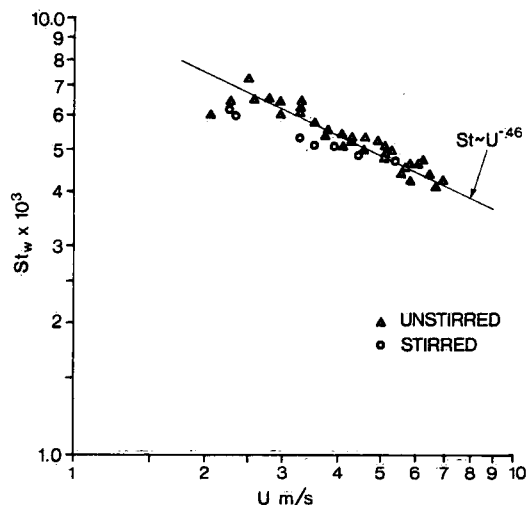

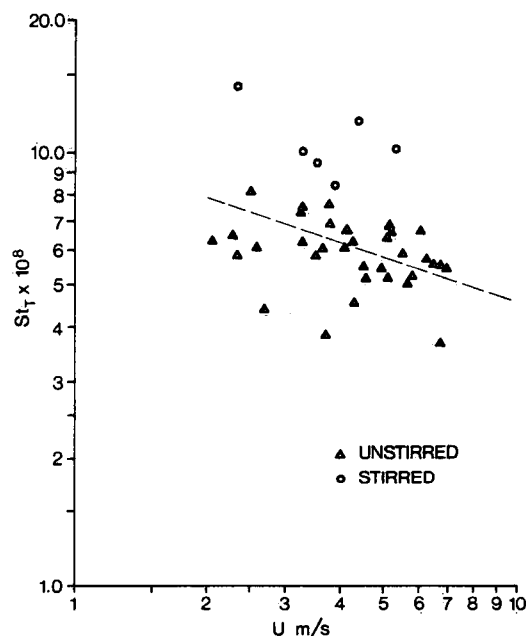Figure 8. Stanton number for water vapour versus wind velocity.

Figure 9. Variation of Stanton number for tritium flux with wind velocity.

The ratio between the Stanton numbers St_t and St_w is plotted in Figure 10 against wind velocity. The ratio is relatively constant for all the unstirred runs. For the stirred runs the ratio is about twice as large, indicating that turbulence in the water increases the tritium flux relative to the water vapour flux which, as shown in Figure 8, was not affected by the stirring.
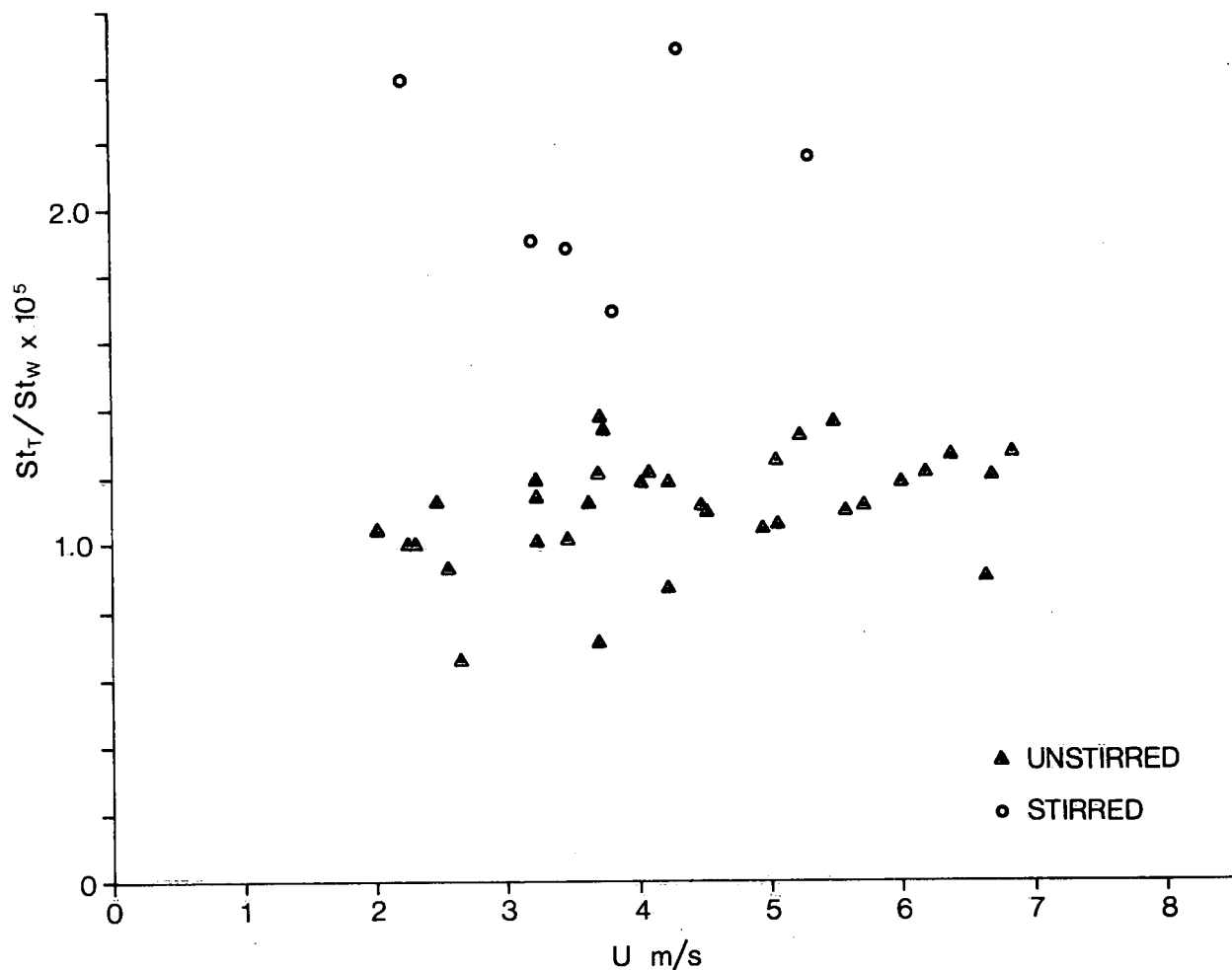
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Figure 10. Ratio between Stanton numbers for tritium and water vapour flux.

APPLICATION FOR FIELD MEASUREMENT OF EVAPORATION

Having obtained a ratio between the wind functions ψ_w and ψ_t from laboratory experiments, one must now consider how this information may be used in conjunction with field experiments to determine the evaporation rate from a river.

The evaporation rate of tritium in a stream can be obtained by releasing a known quantity of the substance into the flow and then sampling at a number of locations down-stream to obtain the concentration distributions. The tritium concentration decreases down-stream owing to in-stream dispersion as well as transfer to the atmosphere. The in-stream dispersion can be accounted for by the use of another tracer such as dye and therefore the tritium flux to the air can be calculated. A value for ψ_t can thus be obtained for that particular stretch of river.

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Using this value of ψ_t, a value for ψ_w can be calculated from the equation

$$\psi_w = r\psi_t \tag{11}$$

where r = the ratio ψ_w/ψ_t determined from the laboratory experiments for that particular condition of turbulence in the water. This value of ψ_w can then be used together with temperature and humidity measurements to calculate the water evaporation rate from equation (1), i.e.

$$E_w = \psi_w \rho_w (P_w - P_a) \tag{1}$$

It should be noted that because the air velocity and direction are in general different from the water velocity, the parcel of water containing tritium is almost always exposed to air with zero tritium concentration. The conditions for tritium flux are therefore similar to the laboratory model shown in Figure 2 in which an air stream with uniform humidity profile and zero tritium concentration flows over a body of water containing tritium.

For the water vapour flux, the laboratory model corresponds to the case of air over dry land blowing across a river. In this instance the humidity profile in the approaching air stream should be uniform and ψ_w obtained from equation (11) should be fairly accurate. However, if the river is very wide or if the wind is blowing along the river, a water vapour boundary layer builds up along the fetch, similar to open water or lake conditions in which both ψ_w and P_a are functions of height, although the vapour flux given by equation (1) can still be considered constant in the lower part of the boundary layer. Under these circumstances, the conditions for water vapour flux are not exactly similar to the laboratory model, and when a value of ψ_w is obtained from equation (11), one cannot say for sure at what height this value should be referred to for the calculation of the evaporation rate. However, from a practical standpoint it can be seen that the value of ψ_w varies only very slowly with height. Using some of the theoretical equations for the profile coefficient ψ_w, such as those proposed by Kitaigorodskiy and Volkov (1965) or by Brutsaert (1975), it can be shown that the values of ψ_w vary by only a few per cent over as much as 10 m. For example, Brutsaert's equation for rough surface is

$$\psi_w (Z) = \frac{U_*}{7.3 \left(\frac{U_* Z_0}{\nu}\right)^{\frac{1}{4}} \left(\frac{\nu}{D}\right)^{\frac{1}{2}} + \frac{1}{K} \ln \frac{Z}{Z_0} - 5} \tag{12}$$

where $U_* $ = shear velocity

Z = height above surface

Z_0 = roughness length

ν = kinematic viscosity of the air

D = molecular diffusivity of water vapour in air

K = von Karman constant

Using a value of 30 cm/s for U_* and Z_0 equal to 0.01 cm, the values of ψ_w at heights of 10, 15 and 20 m are 0.981, 0.950, and 0.929 respectively. The value of ψ_w varies by only 3.2% between 10 m and 15 m and by 5.3% between 10 m and 20 m. The error involved may not be very large if the value of ψ_w calculated from equation (11) is assumed to be equal to ψ_w at, say, 15 m. The evaporation rate calculated using this ψ_w and vapour pressure at 15 m is likely to be overestimated by a few per cent, however, this kind of error is not excessive in view of the fact that no other suitable method is available for estimating the evaporation for a stretch of river.

SUMMARY AND CONCLUSIONS

1. For the present experimental set-up the value of the wind function ψ_w appeared to increase linearly with wind velocity. The ψ_w values did not seem to be affected by turbulence in the water created by stirring.

2. The wind function for the tritium ψ_t also increased more or less linearly with wind velocity. The scatter was rather large, however, owing mainly to the small changes in water depth and tritium concentration, which leads to large uncertainties in the data analysis.

3. Wind function ψ_t was greatly increased by stirring of the water, indicating that turbulence in the water increases the tritium flux significantly.

4. The ratio ψ_w/ψ_t was relatively constant for wind velocities varying from 2 to 7 m/s, indicating that both ψ_w and ψ_t are affected to the same extent by increased turbulence in the air, however, ψ_w/ψ_t was much larger when the water was stirred.

5. The effect of turbulence in the water on ψ_w/ψ_t must be quantified by further laboratory experiments. The feasibility of measuring river evaporation by radioactive tracer depends on the success of these experiments. One possibility is to use the average vertical diffusion coefficient, which can be measured both in the field and in the laboratory, as the indicator of water turbulence.

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6. Experimental scatter can be reduced by incorporating temperature and humidity controls for the incoming air and by suitable modifications that would allow test runs of longer duration. Water evaporation may be measured by noting the amount required to maintain a constant level, thus maintaining a constant effective wind velocity throughout the experiment. Improved tritium measurement techniques may also be available.

7. So far, tritium was the only tracer used. The use of other tracers, such as krypton, ought to be investigated.

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