AN EXPERIMENTAL STUDY OF RADIOACTIVITY DISPERSION IN OPEN CHANNELS

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ABSTRACT

The work has been an experimental and numerical investigation of radioactivity risk assessments using tracer test technique in open channel flow. Two types of tracer have been used and then examined, pure KCl which has dual indicator at the same time electrical conductivity and radioactivity, and Carmosine (E-122) a florescence dye which used for environmental safety requirements. Thirty three runs were performed to measure solute transport in open channels flows and calculate doses that response from these concentrations. ADE models for one and two dimensional of cases instantaneous and continuous injections in steady states were applications and shown good agreement between predict and observed concentration of the mixing in the flume. The analyses and comparisons show the average MRE equal to 7.2 %, and discrepancy ratio between observed and predict of $\varphi = 45$ equal to 2.66% & r^2 equal to 0.984.

KEYWORDS

Dispersion in open channel, Radioactivity dispersion

LIST OF SYMBOLS

A The number of radioactivity nuclei remaining at time t. $\left(\frac{Bq}{L}\right)$.

A_o Original number of radioactivity nuclei $\left(\frac{Bq}{L}\right)$.

C Concentration of solute. mg/L

D Longitudinal dispersion coefficient , (m^2/s)

d Depth of water , m

M Mass of solute (kg/L)

K_y Transverse mixing coefficient , (m^2/s)

u Velocity of flow, m/s.

u_* Shear velocity , m/s

τ_0 bed shear stress on the channel bottom, N/m^2.

ρ the density of the fluid, kg/m^3.

x distance ,m

INTRODUCTION

Rising industrial and domestic use of water, combined with greater public and Governmental interest in the environment, means that the problem of predicting solute transport in rivers is of increasing importance.

Engineers may be faced with predicting the result of accidental spillages of chemicals (radioactive material) or setting the level of discharges from a pollutant source. Whatever the specific application, there is a need for reliable models of solute transport in open channel flows and calculate doses that response from these concentrations. In solute transport models, the velocity and dispersion coefficients in the channel must be known. Dispersion coefficients represent all the mixing processes in the flow. (Fischer, 1979)[1]. Longitudinal dispersion coefficient can be estimated directly using tracer test technique (Rutherford, 1994)[2] or by major factors of dispersion characteristics which can be categorized into three groups;

1. Fluid properties; included fluid density and viscosity.
2. Hydraulic characteristics; cross-sectional mean velocity, shear velocity, channel width, and depth.
3. Geometric configuration; the bed form and sinuosity.(Won, 1998)[3]

Contamination of water and the consequent human health risks associated with the contamination of radioactivity are serious ongoing problems. It is generally accepted that for any contaminant release, there are questions need to be addressed which are most succinctly stated as:

1. How long will it take for the contaminant to reach the receptor?

2. At what concentration level(s) will the receptor be contaminated?

3. For how long will the contamination persist?

4. Which points that receipt first concentration in the bank sides?

5. Are these concentrations exceeding maximum permissible concentration?

The work described in this paper is an experimental and numeric investigation of the transport of solute in a simple open channel flow that incorporates these data.

SOLUTE MIXING IN OPEN CHANNEL FLOW

The concentration of a solute in a flow will, obviously, depend upon the nature of the source of the solute. The concentration of the solute as it enters the flow, the duration of the discharge of solute and how the solute enters the main flow, for example as a diffuse or a point source, will affect the concentrations measured downstream of the solute source. It is useful to split discharges of solute into two groups: continuous discharges and time varying discharges. For a continuous discharge of a solute into a flow the concentration of solute in the channel, after it has spread over the whole cross-section, can be predicted from a simple mass balance. For this case an understanding of longitudinal dispersion is not necessary. However for an instantaneous or time varying input of material

to the channel an understanding of longitudinal dispersion is essential.

Consider an injection of a mass of dye into a long straight channel, as sketched in Fig.(1). Three stages of mixing can be identified:

(***A***) the initial momentum and buoyancy of the discharge determine the rate of dilution.

(***B***) As the dye is transported downstream, cross-sectional mixing caused by secondary currents, turbulence and molecular diffusion (which typically turbulent diffusion coefficient of order of 10^{-3} and molecular diffusion coefficient $10E-9\ m^2/s$) tends to spread it over the depth and the width.

(***C***) As the dye spreads vertically and transversely it is exposed to the vertical and transverse velocity profiles. The difference between the stream wise velocities of two adjacent dye masses (shear flow dispersion) tends to spread the tracer cloud longitudinally; this effect is termed differential advection. [Fischer, 1979][1] [Rutherford, 1994][2]

Taylor's analysis of longitudinal dispersion in pipes could be applied to the last stage, but there is an equivalent analysis for longitudinal dispersion in rivers. Vertical and transverse mixing profiles are sketched in Fig.(2), showing idealized (uniform) velocity profiles.

Turbulence is also thought to be generated in zones of high shear, which in a river would be found near its bed. From dimensional

analysis, a relationship that describes the strength of the shear is given by the shear velocity:

$$u_* = \sqrt{\frac{\tau_0}{\rho}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where τ_0 = bed shear stress on the channel bottom, N/m^2.

ρ = the density of the fluid, kg/m^3.

In uniform open channel flow, gravity balances friction and the shear velocity may be expressed as a function of the depth, slope and gravity as:

$$u_* = \sqrt{gdS} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Turbulent diffusion coefficients,D, are then found to be proportional to the product of river depth and shear velocity: as shown in Table (1)

$$(D \text{or} k_y) \propto d * u_* \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

By making certain assumptions it is possible to derive an equation for the change in cross-sectional average concentration following a discrete input of solute to a uniform flow. The equation is only valid after the solute is well mixed in the flow and predicts that eventually the spatial distribution is a Gaussian whose variance increases linearly with time as the dye is transported downstream. It was developed by Taylor and Fischer and is known as the Advection Dispersion Equation (ADE). The ADE has the same form as a diffusion equation, but the

dispersion coefficient in the ADE includes the effect of diffusion, turbulent mixing and differential advection.

RADIOACTIVITY

The activity of radio isotopes source is defined as its rate of decay, and is given by the fundamental law of radioactive decay,

$$-\frac{dA}{dt} = \lambda n \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where A = The number of radioactive nuclei remaining at time t.

λ = Decay constant,

The negative sign indicating a decrease. By integration we get;

$$A = A_0 e^{-\lambda t} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where A_0 is the original number of radioactive nuclei. [Durance, 1986][4]

SOLUTE TRANSPORT MODEL IN OPEN CHANNEL

Numerous model variations designed to describe solute transport have been developed. A general advection-dispersion equation (ADE) typically appears as:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} + k_y \frac{\partial^2 C}{\partial y^2} - u\frac{\partial C}{\partial x} - \lambda c \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Initial dilution near the point of discharge is usually controlled by the momentum effects of jets.

The transfer of mass due to convective motion in the x-direction given by the term $u\frac{\partial C}{\partial x}$ is called longitudinal convective, while the differences in the longitudinal convective, mass transfer which is associated with the actual velocity distribution, is known as longitudinal dispersion, which is the dispersion term $D_x\frac{\partial^2 C}{\partial x^2}$. Transverse mixing coefficient with mass transfer in the y-direction is formulated in term $k_y\frac{\partial^2 C}{\partial y^2}$. The developments analytical ADE using laplace transform technique are described in Ref.[Bruce, 1999][5], the solution of these cases is presented in the following Eqs.

$$C(x,t)=\frac{M}{A\sqrt{4*\pi*D*t}}\exp\left[-\frac{(x-u*t)^2}{4*D*t}-\lambda*t\right] \quad \text{.....(7)}$$

The boundary conditions of this equation are:
(Instantaneous input mass of solute (M) at time $t=0$ & at $x=0$), ($C=0, x=\infty, t>0$), ($\partial C/\partial x=0, x=0,\ t>0$).

$$C(x,y)=\frac{Q_0}{2\pi*d\sqrt{D*k_y}}\exp\left(\frac{u}{2D}-\frac{\lambda_i*x}{u}\right)*K_0\left[\frac{u}{2*D}\sqrt{x^2+\frac{D}{k_y}(y-y_0)}\right] \quad 8)$$

The boundary conditions of this equation are:

(a constant concentration C_0 is maintained at $x=0, t\geq 0$), $C=0, x>0, t=0$),($C=0, x=\infty, t\geq 0$).

The analytical solutions are compared with the results of experimental works .

EXPERIMENTAL WORK

The experimental work is carried out at the hydraulic laboratory of the Engineering college at AL-Mustansiriyah University and the laboratory tests were some conducted in Environmental Research and Toxic Material Department of the Sciences and Technology Ministry to provide more detailed information about the characteristics of radioactivity mixing in open channel.

All of the experiments were performed in a flume (20 m) long, wide (0.9 m) and it constructed of steel structure with Perspex panels walls of (1.2 cm), and the effective wide is 0.85m. Water was pumped by an electrically driven centrifugal provide a maximum flow of ($13 L/s$) to the flume from the laboratory sump tank ($3.5 m^3$) and four small pumps with ($0.5 L/s$); the Discharge was regulated by a 4 inch gate-valve. The entrance to the flume was filled with filter material (multi short lengths of mesh wire 12mm) which served to break up any large eddies in the flow, water from the main sump under the laboratory flume was pumped at a fixed rate up to the header tank and entered large tanks at the end of the flume.

A bed of plastic covered with 12mm broken gravel with a slope of 1:1416 was laid in the flume, the slope was chosen as representative of a natural open channel flow with the aspect ratios that could be obtained in the flume, as shown in plate(1). Twenty five runs (L1-25) are performed with different flow rate that varied between 0.5 and 12.5 L/s. Pure KCl salt has been used as main tracer in this study as indicator of conductivity and radioactivity in water. A small fraction (0.0117%) of natural potassium is radioactive ($K-40$). The processes of radioactive decay of $K-40$ produce gamma rays of just one energy 1461 KeV, with a specific activity ($31\ kBq/Kg$) of $K-40$. [User Guide, 1979][6].

Carmoisine(E-122) commercial synthetic dye food India production was used also as tracer in this study. The Carmoisine was found under sensitive to radioactivity instrument.Injection solutions were prepared to a conc. of ($300\ g/L$) by dilution of the KCl ($150\ g$) with ($0.5\ L$) tab water, for Carmoisine ($25\ g/L$) using electrical mixer to dissolve solutions, These masses has been chosen theoretically that responsible to sensitive of instruments measurement reading[Field, 2003][7]. The solution was added quickly with a sharp cut off (one second); so that it travels downstream in a cloud.

The flume sampling at mid (9 and $18m$) (a few of experiment has been taken at $13.5\ m$) from the injection point in two methods manual and direct measured through conductivity cell, using

DVD digital video camera record the time of manual samples for carmoisine or specific conductance through the visual indication data logger display, then using computer program (Ulead Studo 2005) convert movie to photo capable to divide sampling time to one second record, all data put in Excel program then converted from $EC(mS/cm)$ to conc. (mg/L) or (Bq/L) and subtracted from background conc. to calculate dispersion performance, for manual method the sampling through a $(12mm)$ internal diameter a glass vials in the continuous mode for carmoisine, the same step above used to calculate concentration dispersion.

Radioactivity of KCI

The radioactivity of KCl solutions were measured by a Gamma spectrometer system, as shown in plate(2).

The Gamma spectrometer system has been calibrated with KCl using prepared solutions over a range of (1.33-200 g/L), It has been prepared using dilution method (for example; weight (200 g) pure KCl add in flask (1 L) distilled water produced (200 g/L) this solution was measured in gamma-ray NaI(Tl) detector with time (1000 s), The net counts per second was recorded and error RSD, at the same time all samples was measured in EC meter, then carefully add (0.333 L) to solution to be (200 g/L) and go on measuring. The total samples of calibration curve were sixteen (R1-R16), gamma background at laboratory site was determined with Marinelli beaker filled with

distillate water, which equal to (0.05682 *c.p.s.*). It has been later subtracted from the measured gamma Ray spectra of each sample. It was observed that the gamma emission was a linear function of conc. with range (1.33-200 g/L):

$$KCl\ Radioactivity(Bq/L) = 15.507 * KCl(g/L) - 40.855 \quad \text{.....} \quad (9)$$

With determination coefficient ($r^2 = 0.9714$).

Also, four samples (F1-F4) have been taken randomly from flume and tested at the same time in Electrical Conductivity , EC instrument and Gamma spectra system to check the transformation approach.

All flume samples have been converted from EC specific conductance (mS/cm) to radioactivity (Bq/L) by calibration curve, as below function this equation with concentration. $< 20\ g/L$) and $EC < 13.22$ effect of net KCl, if the concentration exceed it take directly interpolation from table;

$$Radioactivity(Bq/L) = 0.0201 * EC^4 - 0.1843 * EC^3 - 1.4426 * EC^2 + 28.157 * EC - 0.5641$$

With determination coefficient ($r^2 = 0.9884$) ..... (10)

Carmoisine (E-122)

The concentration of Carmoisine dyes were measured by a (PYE unicam sp6-350 visible spectrophotometer manual scanning type Philips) in visible wave length. The spectrophotometer was calibrated using prepared solutions of known concentration over a range of (1-600 mg/L), It has been

prepared using weighting method (for example; weight ($0.01\,g$) powder add in flask ($1\,L$) tab water produced ($10\,mg/L$) .

It was observed that the color absorption was a linear function of the tracer conc. with conc. range (0-350 mg/L) ($r^2 = 0.999$):

$$Concentration(mg/L) = 363.43(Absorbance) + 2.7695 \quad \ldots\ldots\ldots (11)$$

The color absorption functions with conc. (350-600)($r^2 = 0.9858$):

$$Conc.(mg/L) = 13576*(Abs.)^3 - 44728*(Abs.)^2 + 49345*(Abs.) - 17819 \quad \ldots\ldots\ldots\ldots\ldots (12)$$

RESULTS AND VERIFICATION

One Dimensional Instantaneous Injection:

The numerical values of the parameters needed to operate the analytical models (M , A, D , x , t , u , and λ) were substituted as; ($M = 150g$, A ($0.0102 - 0.051$) , $D = 17.018*du_* + 0.0035$, $x = 18m$, $t\,(1 - 1200s)$, u ($0.043 - 0.247m/s$) and λ for $k - 40 = 1.28*10^9\ yr$.).

The flume sampling position ($18m$) for all observed data has been calculated as cross-sectional average conc., to be accurate with ADE. .(Rutherford, 1994)[2]

A typical plot of KCl radioactivity conc. in flume compared with analytical model shown in Fig.(3), and regression analysis in Fig.(4).The Figs.(3) and (4) shown as below :

1. All observed data (L1-L25) have skewness and kurtosis larger than ADE, that is mean BTCs of observed data were inclined to the right and downward comparison to ADE, that's because the effect of dead zone. Dead zones are regions of the flow within which the tracer material can become temporarily trapped, and from which tracer is gradually released back into the main flow. Dead zones have been considered to be produced by the voids between individual stones of a gravel bed.
2. The analyses and comparisons show the average median relative error (MRE)equal to 8.84 %, and for average verification analyses of angle equal to 3.7% & r^2 equal to 0.96, that's agreement of ADE according to (Thomann, 1982)[8].

COMPARISON BETWEEN KCL AND CARMOISIN TRACERS:

There are differences between KCl , (run K1-K2) and Carmosine, (run C1-C2) concentration along flume ; the reason was that carmosine in manual sampling and the duration of two series samples of range (3-7 s), in the other side KCl measurement reading every second.

Limitations in absorbance instrument measure (0-400 mg/L) with absorbance (0-1), where absorbance excess (1) it convert

concentration from liner to non-linear Eq. and stop reading in (1350 mg/L). In other side EC meter has large range (0-25000 mg/L), therefore, the Carmoisine run have been done in these range to avoid error in measurements reading.

The comparison between these run have be done in Table(2), with respect to one dimensional ADE, these results show KCl more accurate than Carmoisine.

TWO DIMENSIONAL MODELS CONTINUOUS INJECTION

Eight data sets obtained from experimental work have been performed to study the flow in two dimensional directions. Results of radioactivity concentration in flume were compared with resultes of analytical model as shown in Figs.(5) and (6).

The data needed for model are; Initial injection of mass flow rate (Bq/s), flume discharge, transverse mixing coefficient, flume velocity, depth, width, and the wide distance of injection according to left bank.

The analyses and comparisons show the average MRE equal to 7.2 %, and discrepancy ratio between observed and predict of $\varphi = 45$ equal to 2.66% & r^2 equal to 0.984, that's agreement of ADE according to,[Helsel, 2002][9] [Thomann, 1982][8].

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CONCLUSION

Measurements of the temporal concentration distribution of a solute tracer within an open channel in one and two dimensional flow have been performed. Two types of tracer have been used, pure KCl and Carmosine (E-122) as indicators of radioactivity in water. Application of analytical advection-dispersion equation, ADE in two dimensional has been deducted to comparison with measured data. Thirty three data sets of experimental work have been verified this study. These comparisons have been shown good agreement between observed and predict concentration of mixing in flume.

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Table (1) previously measured values of longitudinal dispersion coefficients in flume. [Rutherford, 1994][2] [Moores, 1996][10]

Fischer (1966)		(Miller, 1974)		(Valentine, 1979)		(Moores, 1996)	
du_* (m^2/s)	D (m^2/s)	du_* (m^2/s)	D (m^2/s)	du_* (m^2/s)	D (m^2/s)	du_* (m^2/s)	D (m^2/s)
0.00291	0.043	0.00381	0.052	0.00205	0.0101	5.23e-4	0.024
0.00377	0.058	0.0067	0.262	0.00340	0.0113	8.36e-4	0.073
0.00449	0.0785	0.00675	0.067	0.00496	0.0125	1.191e-3	0.120
		0.00821	1.263	0.00764	0.0147	1.62e-3	0.172
		0.01461	1.08	0.01231	0.0186	1.76e-3	0.111
		0.01464	0.148	0.02506	0.0268	2.12e-3	0.198
		0.02138	6.128	0.05968	0.0349	3.88e-3	0.261

Table(2) Comparisons between KCl and Carmoisine concentration.

Exp. No.	Velocity by Tracer test m/s	Dispersion Coeffient m^2/s	MRE % between Observed and perdict
C1	0.12	0.009	14.2
C2	0.1679	0.02127	17.5
K1	0.125	0.01	6.9
K2	0.1781	0.01939	9.5

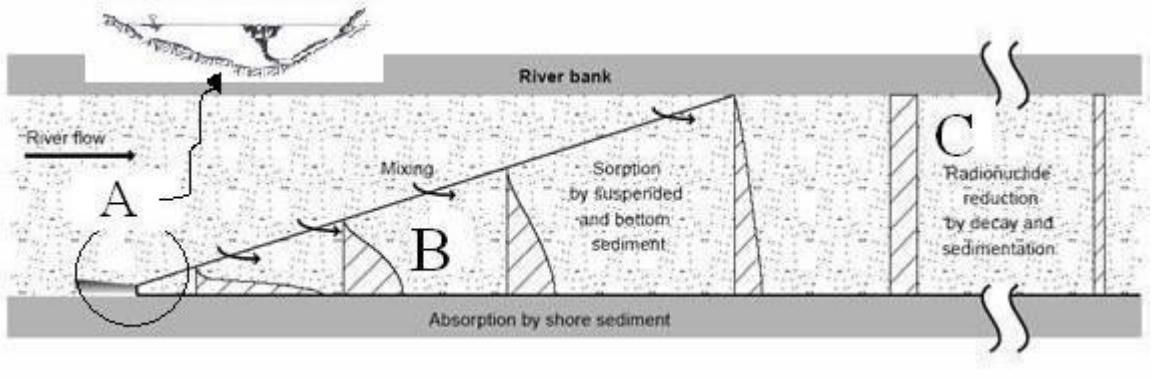

Fig.(1) Stages of mixing. [Fischer, 1979][1] [IAEA, 2001][11]

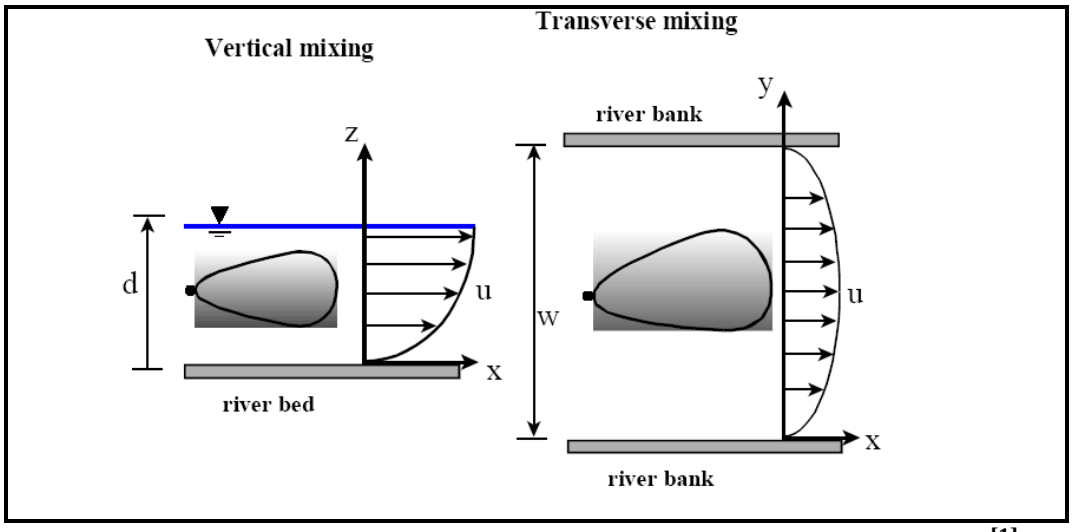

Fig.(2) Vertical and transverse mixing[Fischer, 1979][1]

Plate (1) General view of the flume.

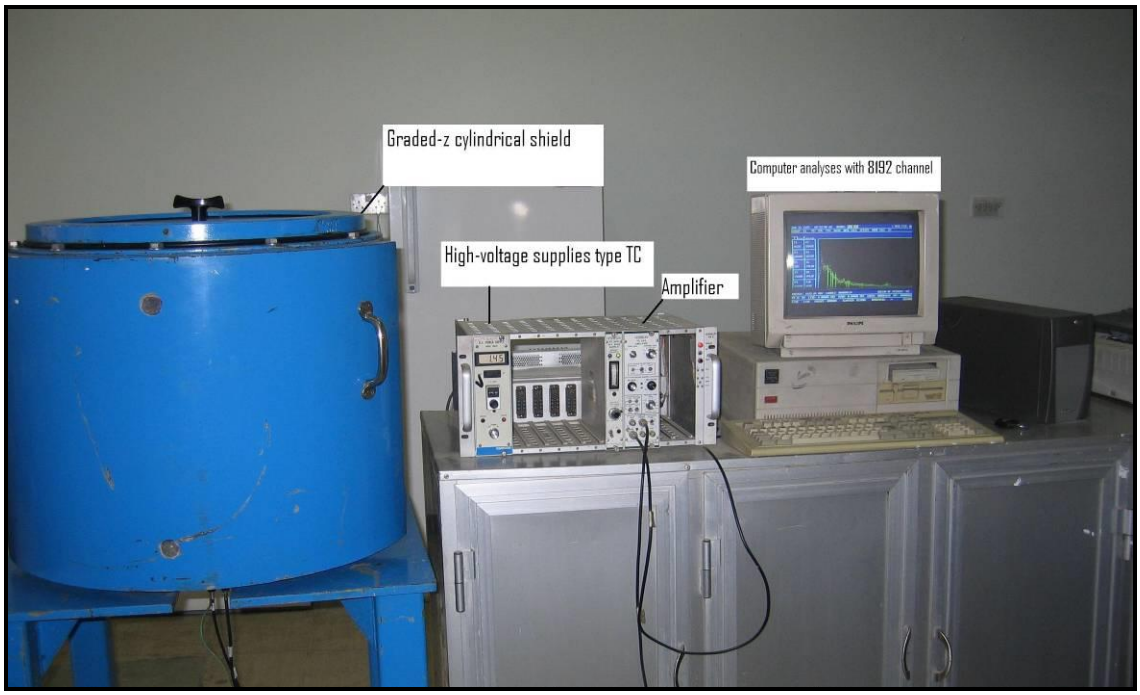

Plate (2) Gamma spectrometer system detector NaI(Tl).

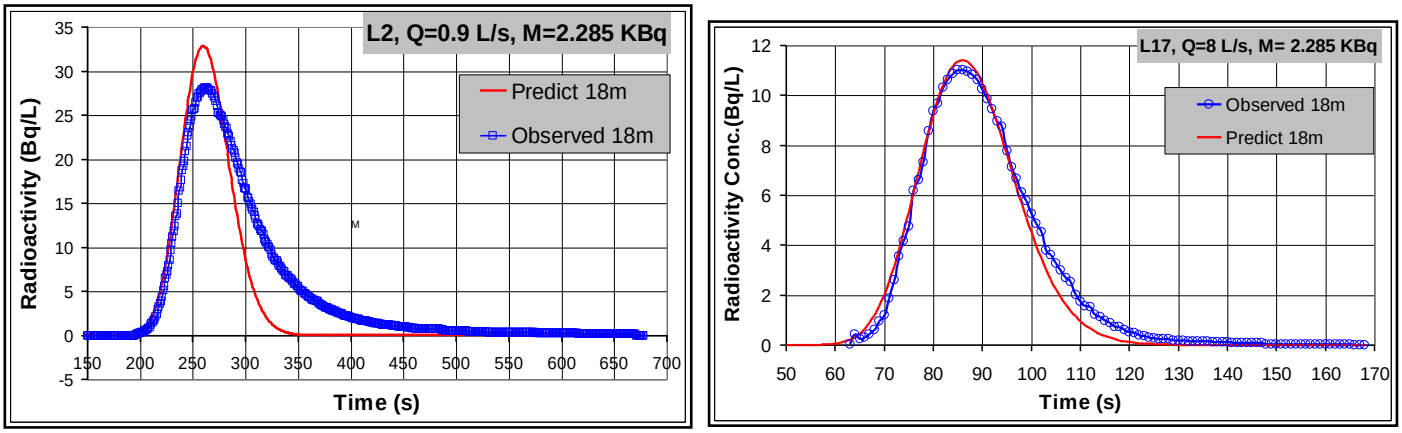

Fig. (3) Comparison between observed and predict radioactivity concentration.

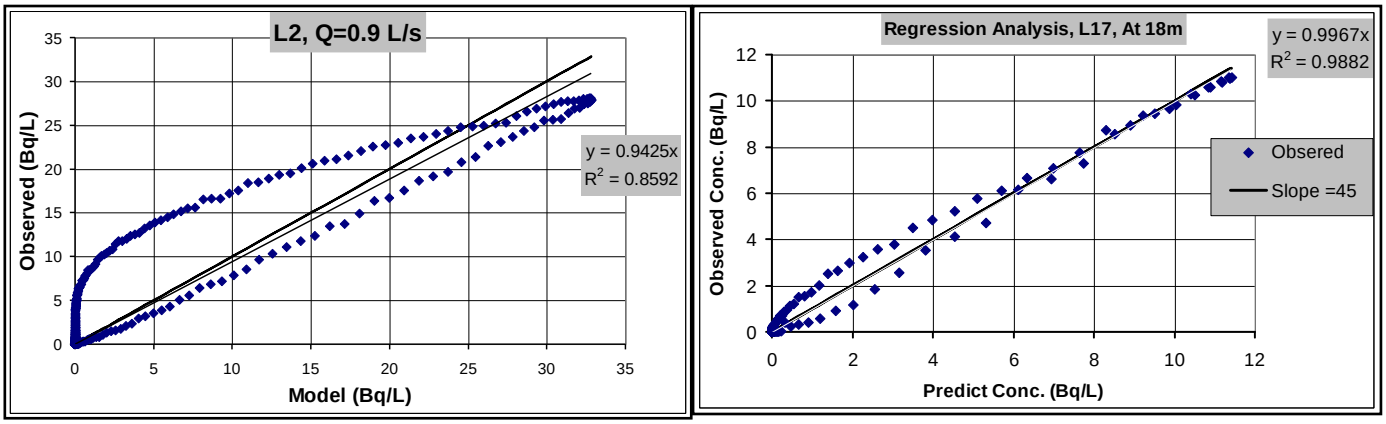

Fig. (4) Verification between observed and predict radioactivity concentration.

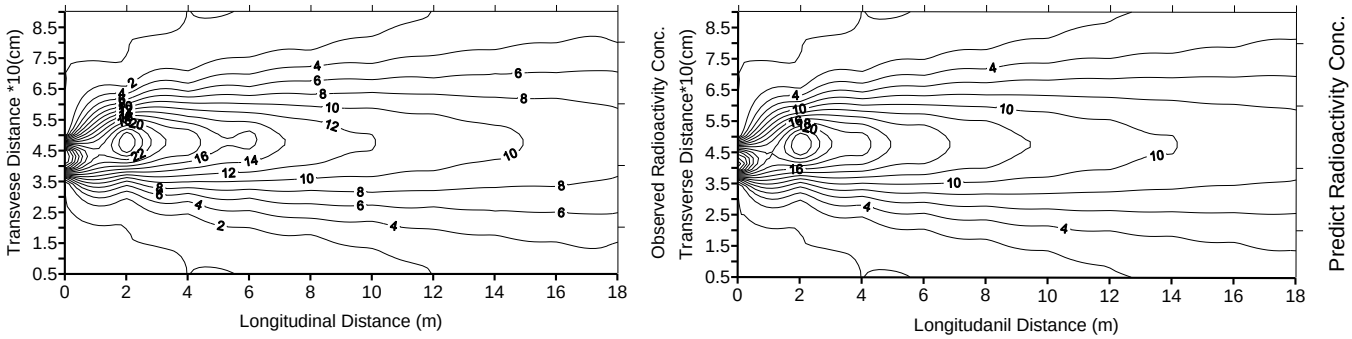

Fig.(5) Comparison Between observed and predict radio-activity conc. In Longitudinal and transverse Distance, Q=10.05 L/s.

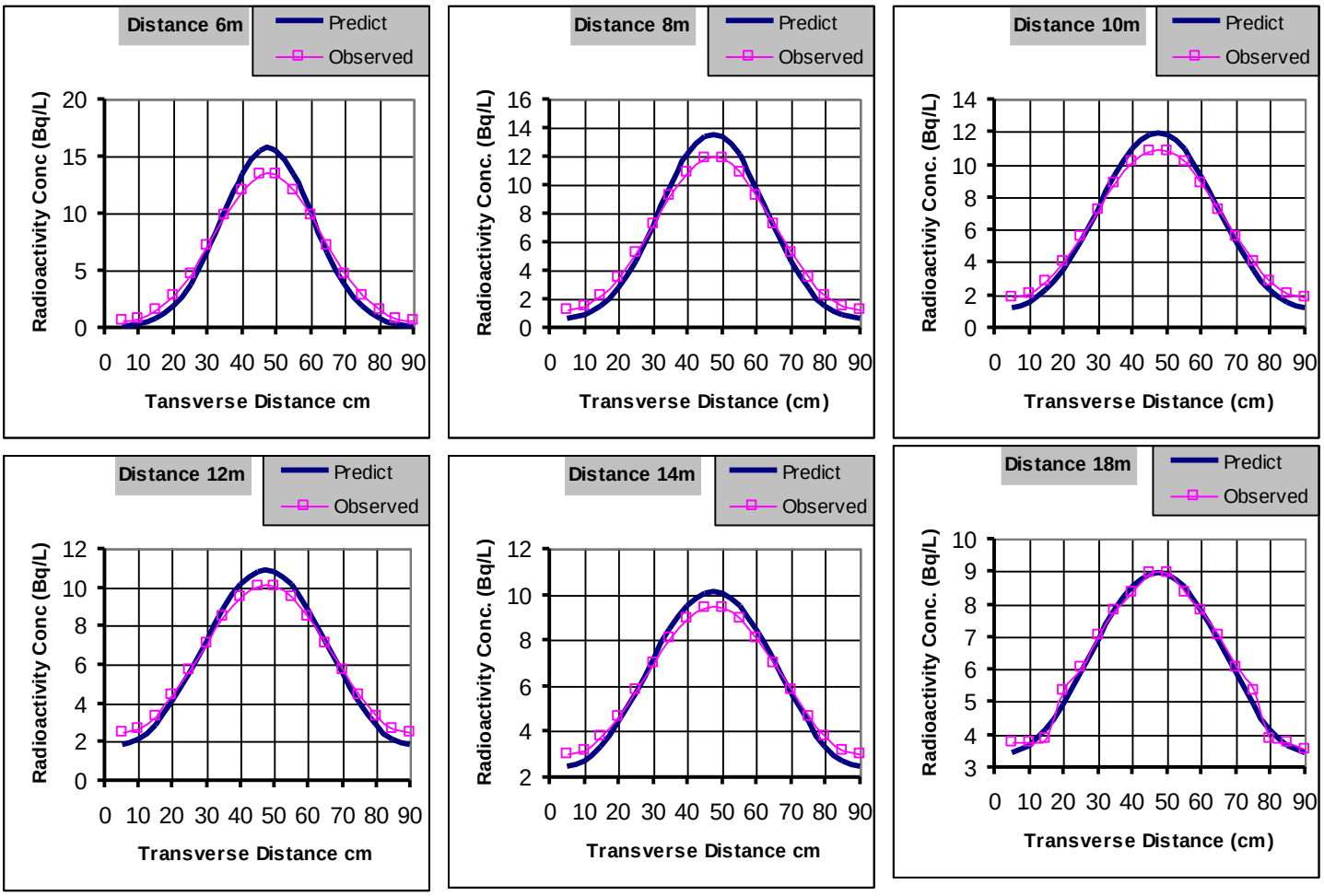

Fig. (6) Comparison between observed & predict conc. in transverse profile., Q=10.05 L/s

دراسة مختبرية لأنتشار الاشعاع في القنوات المفتوحة

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الخلاصة

تم أجراء عمل مختبري وتكهن رياضي لتقدير انتشار الملوثات الاشعاعية باستخدام تقنية الاثور الذائبة بالماء في القنوات المفتوحة . استخدم نوعين من الاثور ومن ثم القيام بفحصها وهما ملح كلوريد البوتاسيم الذي يملك خاصيتين للتحسس في نفس الوقت التوصيلة الكهربائية والنشاط الاشعاعي وصبغة الكارموسين الملونة التي استخدمت كمتطلب للأمان البيئي . اجريت ثلاث وثلاثون تجربة مختبرية لقياس انتقال المحلول في القناة المفتوحة ومن ثم تم حساب الجرعات الاشعاعية الناجمة عن تلك التراكيز. طبقت نماذج رياضية ADE ذات البعد الواحد والبعدين لحقن آني ومستمر ثابت وقد أظهرت النتائج توافق جيد مابين التراكيز المقاسة في القناة والتراكيز المستحصلة من النموذج الرياضي . من خلال نتائج المقارنة ان معدل الخطأ النسبي (MRE) يساوي 7.2% ونسبة الانحراف بين المقاس والمحسوب هو بحدود 2.66% ومعامل الارتباط بقيمة 0.984 .

الكلمات الدالة

التشتت في القنوات المفتوحة, التشتت بالاشعاع