Appropriate Technology for Sustainable Rainwater Harvesting Based on Optimal Rainfall Estimates

Geoffrey Openy[1], Albert I Rugumayo[2], Max Kigobe[3]
[1]Graduate Student Faculty of Technology, Makerere University P.O.Box 7062, Kampala, Uganda
Corresponding author email: gopeny@gmail.com
[2] Senior Lecturer, Faculty of Engineering, Ndejje University P.O.Box 7088, Kampala, Uganda
[3] Lecturer, Faculty of Technology, Makerere University P.O.Box 7062, Kampala, Uganda

ABSTRACT
There is growing interest in rainwater harvesting (RWH) technology as an alternative source of water supply not only in drought prone areas but also in areas which receive abundant rainfall. As such research efforts to simplify rainwater collection in both urban and rural settings are being promoted through various interventions. This study focused on key aspects that are not usually addressed in such interventions, especially in developing countries. These are: i) probabilistic nature of rainfall occurrence, ii) the effects of sparse distribution of rain gauges from which rainfall data is collected and iii) use of daily rainfall averages in sizing storage tanks. A method that takes these factors into account is developed through the analysis of the available rainfall information and the existing RWH practices in Gulu District, Northern Uganda. Rainfall information was established by applying information theory to study rain gauge network within Gulu and the surrounding districts. Relationships between rainfall information and the existing RWH practices and between catchment sizes and storage tanks were established using probabilistic methods. The results show that the dominant RWH practice is the roof catchment systems and catchment sizes range from 100 m^2 to about 600 m^2s. Tank sizes were noted to vary between 500 litres and 10,000 litres. It was noted that the probability of finding water in the existing rainwater tanks when needed, on any given day of the year is about 7%, when the usage rate is limited to a minimum of 20 litres per person per day. The rain gauge network study reveals that a given station can serve an area within 20 km radius. The results show that most roof catchments are small compared to corresponding storage tanks. As a result, most of the tanks remain empty during water stress periods. Based on the above information, an appropriate method for sizing the rainwater tanks was developed.

KEY WORDS: Information Theory, Probabilistic Methods, Rainwater Harvesting,

1.0 Introduction

Rainwater harvesting (RWH) has been an age-old practice of harnessing water for productive uses throughout human history. It has however been limited to dryer parts of the world and neglected in areas with abundant rainfall (Spinks *et al*., 2003). However, the challenges of increasing population, rapid urbanization and climate change putting strains on the available water resources are turning world's attention to explore this ancient practice as an alternative to traditional large engineering solutions not only in drought prone areas but also in areas endowed with abundant rainfall (WWAP, 2009). A number of case studies already exist on RWH technology in developing countries (Ntale *et al*., 2005; Thomas, 2005; Handia *et al*., 2003; Ngigi, 2003). But many of the studies have focused on: policy issues and socioeconomic factors affecting RWH practice and very little has been done to check the reliability of the rain gauges, from which rainfall data are collected.In developing countries, sparse rain gauge distribution does not give proper representation of areal rainfall coverage given probabilistic nature of rainfall (Cowden *et al*., 2008). Rainwater harvesting systems design has been based mainly on monthly rainfall averages (WWAP, 2009; Rugumayo, 1995 and Ntale*et al*, 2005). This only gives approximate sizes of storage tanks as water use is a daily experience.

2.0 STUDY AREA

Gulu and the surrounding districts were chosen for this study because the area experiences acute water shortage despite abundant rainfall, which for Gulu District is second only to Entebbe in intensity (Basaliriwa, 1994). This study is done in two parts: i) evaluation of the existing RWH practices was done in six districts; namely: Gulu, Pader, Kitgum, Lira, Arua and Nakasongola as shown in Figure 1 and ii) evaluation of the raingauge network was done only in Gulu district as shown in Figure 2

Figure1: Six districts covered in the evaluation of existing RWH practices

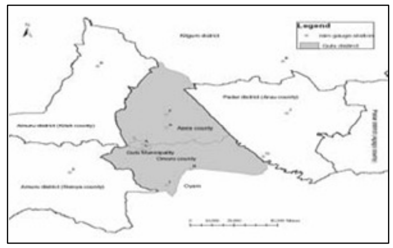

Figure 2: Gulu District covered by rain gauge network study

3.0 INFORMATION THEORY AND HYDROLOGICAL NETWORK DESIGN

In information theory, a measure of the information content associated with the outcome of a random variable is referred to as self-information (Shannon, 1949). The amount of self-information contained in a probabilistic event depends only on the probability of that event: the smaller its probability, the larger the self-information associated with receiving the information that the event indeed occurred. The self-information $I(x_n)$ associated with outcome x_n is given by:

$$I(x_n) = \log_2\left(\frac{1}{P(x_n)}\right) = -\log_2 P(x_n) \qquad (3.1)$$

The expected information would be

$$E[I(x_n)] = -P(x_n)\log_2 P(x_n) \qquad (3.2)$$

Where $P(x_n)$ is the probability of x_n occurring. This measure has also been called surprisal, as it represents the "surprise" of seeing the outcome (a highly probable outcome is not surprising). These expressions measure information content in units of information: *bits* if the base of the logarithm is to base 2, *nats* if the base is e and *hartleys* if the base is 10.Shannon (1949) referred to the expected information (Eq.2) as the entropy and defined it as follows: The entropy; *H(x)* for a set of respective discrete and continuous probabilities $p(x_n)$ is given by:

$$H(x) = -\sum_{n=1}^{N} p(x_n)\log_2 p(x_n); \qquad n=1, 2, 3\ldots N \qquad (3.3)\text{ a}$$

$$H(x) = -\int_0^{\infty} p(x_n)\log_2 p(x_n)dx; \qquad n=1, 2, 3\ldots N \qquad (3.3)\text{ b}$$

The word entropy which refers to the measure of disorder is commonly used in thermodynamics. The expressions were derived from determining the expectation of self-information. For multivariate distribution, H(x) is the marginal entropy; it indicates the uncertainty in the variate X. If there exists $y_m(m=1,2,3, \ldots)$ related with a random variablex_n, the uncertainty in x_n may be reduced by estimating x_n using y_m. Using thesame principle the remaining uncertainty in X with given Y can be estimated for the respective distributions as follows:

$$\text{H(X/Y)} = \sum_{n=1}^{N}\sum_{m=1}^{M} p(x_n, y_m)\log_2 p(x_n / y_m) \qquad (3.4)\text{ a}$$

$$H(X/Y)=\int_0^{\infty}\int_0^{\infty} p(x_n, y_m)\log_2 p(x_n / y_m)dxdy \quad (3.4)\text{ b}$$

Where $p(x_n, y_m)$ isjoint probability of $X=\{x_n\}$ and $Y = \{y_m\}$. The logarithm to base 2 quantifies the information in bits. The reduction in uncertainty in X with given Y or the trans-information between X and Y is defined as:

$$T(X,Y)=H(X)-H(X/Y) \quad (3.5)$$

In network design this method can be applied to reduce or expand on the existing network. For instance in a given drainage basin an optimum number of rain gauges at representative locations is required to provide data for hydrological studies of the area (Grimes *et al*., 1999). The data that can be collected from such stations provide information on which decisions can be made on water resource development and many other aspects of life that depend on water. For both rain gauge network reduction and expansion, a method based on Shannon's information theory developed by Husain (1989) has been majorly used: Sazakli, Alexopoulos and Leotsinidis (2007); Sarlak (2006);Yoo, Jung and Lee (2008). According to this method, a probability model that fits the area's rainfall has to be known. The model is derived by fitting local rainfall data collected from the existing stations.

4.0 METHODS

4.1 Functional Assessment

A self-administered questionnaire and a thematic checklist were used to carry out functional assessment of the existing RWH facilities. This covered type and size of facility, physical observation of the different components of the facility to assess the functionality of each component. A sample size of 15 was used per district covered. The assessment covered the interrelationships among different components in ensuring maximum collection of rainwater during a rainfall event.

4.2 Representativeness of Rain Gauge Network in the Study Area

Entropy method was used to determine the reliability of existing rain gauge network in providing rainfall information. Daily rainfall data from 11 weather stations for periods from 1937 – 2000, were collected and used in this exercise. Consistency checks of the rainfall data were done by applying double mass curves on data sets. After the checks the daily data sets were fitted on standard probability models. This was done by analysis of the frequency distribution of the data from each station.

4.3 Calculation of Entropy and Transinformation

The model that fitted the data with an error of 5% based on Kolgomorov goodness of fit test; was found to be one parameter exponential function of the form in Equation 1. This was used in calculation of entropies of individual stations and transinformation among stations.

$$f(x)=\xi e^{-\xi x} \quad (4.1)$$

For calculation purposes expressions for entropies and transinformation have been derived for different distribution functions in the literature (Yoo, Jung and Lee, 2008). For the one parameter exponential function the expressions are as followed:

$$H(x)=\ln \xi \quad (4.2)$$

$$T(X, Y)=\frac{1}{2}\ln\left(1-R^2\right) \quad (4.3)$$

$$R=\frac{S_{XY}}{S_X S_Y} \quad (4.4)$$

Where R is the cross correlation coefficient between variables X and Y, S_{XY} is calculated from the covariance between data sets X and Y, S_X and $S_Y$are standard deviations of X and Y respectively.

And $H(x)$ is an expression for entropy, ξ is the distribution parameter which is estimated from the reciprocal of the sample mean, $T(X,Y)$ is the transinformationcalculated using Equation 3.4.

4.4 Sizing of Rainwater Storage Tanks

Analytical functions took considerations of: water use rate, meteorological conditions and reliability of having water when needed were derived using the model of Equation 4.1 according to a method proposed by (Guo and Baetz, 2007, Adam and Papa, 2000). The derived functions were used to plot graphs that relate storage tank sizes and roof catchment at achievable reliabilities. Reliability here is defined as; the probability of having water in a rainwater tank on any day of the year when needed for a given roof catchment system, expressed in percentages. Theanalytical relations derived among interacting variables are shown in the following equations:

$$Ra = \frac{A\theta\Phi}{\xi} e^{-\xi x_{ff}} \tag{4.5}$$

Where *Ra* is total volume of rainwater generated per annum after diverting the first flush; *A* is a given roof catchment area, θ is the annual expected number value of inter event time. The interevent time is the minimum time taken between successive rainfall events.

4.5 Storage Volume Expressed in Terms of Catchment Size

An expression for storage device in terms of the catchment size, use rate and reliability is given by:

$$V = \frac{A\Phi C}{\gamma C + \gamma A\Phi} \ln\left[\frac{\gamma A\Phi}{\gamma A\Phi - Re(\gamma A\Phi - \xi C)}\right] \tag{4.6}$$

Where A = the catchment area in square metres; V = storage volume of the rainwater tank (Cubic metres); C = use rate (litres/day); *Re* = reliability of storage unit in supplying water, defined as the fraction of time when use needs are satisfied by water collected in the storage unit (dimensionless); $\bar{u}$ = average rainfall interevent time (days); $\bar{x}$ = average rainfall average rainfall event volume (mm); Φ = run off coefficient (dimensionless); ξ = parameter for rainfall event depth; γ = parameter for inter event time definition ; θ = annual expected number of the interevent time.

5.0 RESULTS

5.1 Rainwater Tank Types Gutter Characteristics and First Flush Devices

Rainwater tanks across the region are made of mainly PVC materials: over 55% in Arua, Nakasongola and Pader. Meanwhile, in Gulu and Kitgum; it accounts for over 80% of the total rainwater tanks; Hand–dug tank was found only in Nakasongola district. Estimates of the guttering of roof catchments' characterised: by the proportion of the total roof area guttered and the type of the material of which the gutters are made showed that: less than 50% of the rainwater installations had gutters, in many instances the gutters and the tanks are available but not connected; In other cases, there are only rainwater tanks without gutters. A first flush device (a mechanical bypass valve) designed to drain away the first portion of rainwater that is always contaminated by debris, atmospheric dust, fly-ash and/or birds droppings, was found only in Pader district. The absence of these devices could point to the limited technical know-how on the RWH technology as many people still practice the opportunist RWH.

5.2 Use Distribution of Rainwater Harvesting Facilities

All the five districts have over 40% of the RWH facilities for institutional use with Kitgum and Pader taking the lead having over 80% of the facilities. Facilities for residential use were only sighted in Nakasongola and Arua Districts while facilities for communal use are found in Nakasongola, Gulu and Arua Districts. The use distribution variation across the districts seems to be influenced by a number of factors; major ones being: availability of other water sources, few number of iron roofs, seasonal nature of RWH rendering it unreliable, lack of clear government policies on RWH practice, limited scientific work on RWH in those districts and other complex socio – economic factors. However, to determine which factor weighs more than the other requires further study.

5.3 Rain Gauge Network Evaluation

The spatial distribution of the rain gauges where rainfall data were collected is shown in the Figure 3. Rainfall data analysed were collected from these stations.

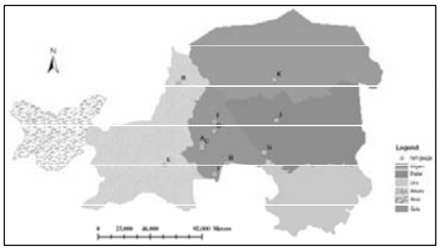

Figure 3: The stations covered in the study

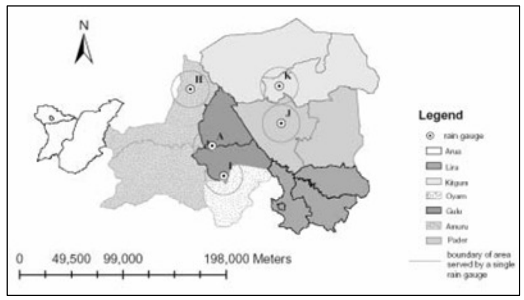

Figure 4: The locations of the five priority station

5.3.1 Selection of Priority Stations

A station is most representative if it has the highest entropy value compared to the rest of the stations. From Table 2, Station A is the first priority station since it has the highest value of entropy. To select the next station, the amount of entropy produced by a given station is added to total sum of transinformation produced by the same station with each of the other stations. This total sum is computed for all the stations in the region and ranked. The first five stations are selected namely, A,H, J,K and I and are shown in Figure 4.Additional Stations are shown in Figure 5.The transinformation contours are plotted in Figure 6. When transinformation–distance curve was plotted, anabrupt change in trans-information was obtained when the distance of the next station is slightly over 20 km as shown in Figure 7. This shows that a given station can only serve a maximum area within 20 km – radius for it to get statistically representative rainfall information.

Table2: Stations arranged in order of priority

Rank	1	2	3	4	5	6	7	8	10	9	11
Station	A	H	J	K	I	F	G	E	C	B	D

5.3.2Relative Sizes of Rainwater Tanks and Catchment Surfaces

Each of the five selected stations is plotted on the same reliability curve to provide comparison among stations. These curves indicate variation in rainfall received at different stations; since it is on the basis of the rainfall amounts for the different locality that storage tanks were sized for different roof catchment areas in each locality.

5.3.3 Existing Rainwater Harvesting Systems compared against Derived Relations

Tables:3, 4 and 5 show situations where analytical relations are used to derive tank sizes for existing roof areas and table at 50% and 10% reliability respectively. The derived relations show that, reliability of the existing RWH systems is below 10%, this is determined from Figure 8(a). Throughout Gulu and the neighbouring districts, this reliability value stands at about 7% which shows that the probability of getting water in the existing rainwater tanks on any given day of the year is about 7%, this is when per capita use rate is limited to the mandatory 20 litres. Figure 8(b) shows that for a higher reliability of 50% the tank size increases. The variation in storage tank sizes across all the districts is between 500 litres to 10000 litres, meanwhile catchment sizes ranges from about 100 m^2 to 600 m^2. Table 6 shows the average tank and catchment sizes for the three districts visited.

Table 3: Existing storage tanks and derived roof area

50% reliability	A	K	J
Tank size(litres)	9057	7900	6357
catchment (m^2)	450	450	250

Table 4: Derived storage tanks and existing roof area

50% reliability	A	K	J
catchment (m^2)	328	146	184
Tank size(litres)	6800	<200	1800

Table 5: Derived storage tanks and existing roof area

10% reliability Stations	A	K	J
catchment (m^2)	328	146	184
Tank size(litres)	1200	100	400

Table 6: Average tank and catchment sizes for the three districts

District	Gulu	Kitgum	Pader
tank size(litres)	9057	7900	6357
catchment(m^2)	328	146	184

Figure5: Additional stations

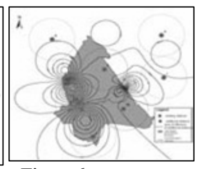

Figure6: Transinformation contours

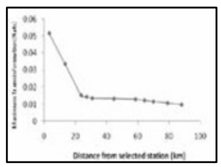

Figure7: Transinformation – distance Curve

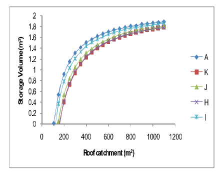

Figure 8(a):10% Reliability

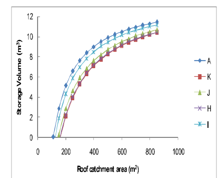

Figure 8(b): 50% reliability

6.0 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Appropriate technology for sustainable RWH was developed through analysis of local rainfall information which is crucial in sizing storage tanks for existing catchments sizes. Analytic relations were derived on the basis of daily rainfall data since water use is daily experience. From the findings, RWH in its present state can only be used to supplement other water sources as roof catchment sizes are not adequate for the existing tank sizes. Furthermore, corrugated iron roofs are constructed purposely for dwellings and RWH practice is a secondary activity if at all it is done. However, for the existing RWH facilities, it is important; as shown by the derived relations, to use smaller tanks no more than 5 000 litres in capacity other than the 10 000 litre tanks that are very common in the areas visited. This is when cost implication is a major constraint, though use of bigger tanks for even smaller catchments can ensure extended periods of rainwater use. From the information theory used to evaluate the rain gauge network, use of rainfall data more than 20 km away from the place where the data is collected leads to inaccurate sizing of rainwater facilities.

6.2 Recommendation

Roof catchment being the dominant RWH practice, requires that policy issues on architectural designs be made to enforce installation of rainwater harvesting facilities on upcoming building designs. This will not only help in cutting water bills for the owners, but will also reduce on the floods that are a big problem in major urban centres of this nation. There is also need to make most of the rundown weather stations functional as this will enable verifications of findings such those in this work, it will also ensure proper water resource planning for the generations to come. Lastly this research needs to be extended to other areas especially in Karamoja area where a number of valley dams were constructed recently to check the reliability of their designs.

REFERENCES

Adams, B. J., and Papa, F. (2000). Urban stormwater management planning with analytic probabilistic models. *Wiley, New York.*

Al-Zahrani, M., and Husain, T. (1998). An algorithm for designing a precipitation network in the

south-western region of Saudi Arabia. *Journal of Hydrology,* 205, 205 – 216
Basalirwa, K. (1994). Delineation of Uganda into climatological rainfall zones using the method of principal component analysis. *International Journal of Climatology,* 15, 116 – 177.
Cowden, J.R., Watkins, D.W.Jr., and Mihelcic.J.R. (2008). Stochastic rainfall modeling in West Africa: Parsimonious approaches for domestic rainwater harvesting assessment. *Journal of Hydrology,* 361, 64 – 77
Grimes, D.I.F., Pardo.E., and Bonifacio, R. (1999). Optimal areal rainfall estimation using rain gauges and satellite data. *Journal of Hydrology,* 222, 98 – 108.
Guo, Y., and Baetz, B. W. (2007).Sizing of rainwater storage units for green building applications.*Journal of Hydrologic Engineering.*12(2) 197 – 205
Handia, L., Tembo, J.M., and Mwiindwa., C. (2003). Potential of rainwater harvesting in urban Zambia. *Physics and Chemistry of the earth,* 28, 893 – 896.
Lee, K. T., Lee, C.D., Yang, M.S., and Yu, C. C. (2000). Probabilistic design of storage capacity for rainwater cistern systems. *J. Agric.Eng. Res.,*77(3), 343 – 348.
Masoumi, F., and Kerachian, R. (2008). Assessment of the groundwater salinity monitoring network of the Tehran region: application of the discrete entropy theory. *Water science and technology,* WST (58.4) 2008.
Ngigi, S. (2003). Rainwater harvesting for improved food security. Promising technologies in greater horn of Africa. Publication of Kenya Rainwater Association.
Ntale, H.K., Naturinda, D.N., Rubarenzya, M.H., and Kyamugambi, K. (2005). The rainwater harvesting strategy for Uganda. *In: Proceedings of 31st WEDC International Conference, Kampala, Uganda, 2005.*
Pardo.E (1998). Optimal selection of number and location of rainfall gauges for areal rainfall estimation using geostatistics and simulated annealing. *Journal of Hydrology,* 210, 206 – 220.
Rugumayo, A.I. Kizza, N. and Shima, J. (2003). Rainfall reliability for crop production, a case study in Uganda. *Diffuse pollution conference Dublin,* 2003 3G. Agriculture, 3 – 143
Rugumayo, A.I. (1995). Rainwater harvesting in Uganda.*Sustainability of Water and Sanitation Systems. 21st WEDC Conference,* Kampala, Uganda, 1995
Sarlak, N. (2006). Evaluation and selection of stream flow Network stations using entropy methods. *Turkish Journal of Engineering and Environmental Science,* 30, 91 – 100.
Sazakli, E., Alexopoulos, A., and Leotsinidis, M.(2007). Rainwater harvesting, quality assessment and utilization in Kefallinia Island, Greece. *Water Research,* 41, 2039 – 2047.
Spinks, A.T., Coobes, P., Dunstan, R.H., and Kuczera.G.(2003).Water Quality Treatment Processes in Domestic Rainwater Harvesting Systems. *The institution of Engineers.Australia 28th International Hydrology and Water Resources Symposium 10 – 14 November 2003, Wollongong, Australia.*
Thomas, T., (1998).Domestic water supply using rainwater harvesting.*Building Research and Information,* 26 (2), 94–101.
World Commission on Dams (WCD) (2009).Assessment of Water Supply Options. WCD thematic review Options assessment IV.3
World Water Assessment Program (WWAP). (2009). Water, a shared responsibility: *The 2nd UN World Water Development Report. UNESCO, Paris and Berghahn Books,* New York City
World Water Assessment Program (WWAP). (2006). Water, a shared responsibility: *The 2nd UN World Water Development Report. UNESCO, Paris and Berghahn Books,* New York City.
Yoo, C., Jung, K., and Lee, J. (2008). Evaluation of rain gauge Network using Entropy theory: Comparison of mixed and continuous distribution; Journal of Hydrologic Engineering, 13(4), 226 – 235

Determining the Reaeration Coefficient and Hydrodynamic Properties of Rivers Using Inert Gas Tracers

James Semuwemba[1], Trevor Elliot[2] and Pauline A. Mackinnon[3]

[1]Postgraduate Researcher, School of Planning, Architecture & Civil Engineering (SPACE), Queen's University Belfast, Belfast BT9 5AG, UK
Corresponding author email: jsemuwemba01@qub.ac.uk
[2]Reader, School of Planning, Architecture & Civil Engineering (SPACE), Queen's University Belfast, Belfast BT9 5AG, UK
[3]Senior Lecturer, School of Planning, Architecture & Civil Engineering (SPACE), Queen's University Belfast, Belfast BT9 5AG, UK

ABSTRACT
Various contaminants which can be aerobically degraded find their way directly or indirectly into surface water bodies. The reaeration coefficient (K_2) characterises the rate at which oxygen can transfer from the atmosphere across the air-water interface following oxygen depletion in a water body. Other mechanisms (like advection, dispersion and transient storage) determine how quickly the contaminants can spread in the water, affecting their spatial and temporal concentrations. Tracer methods involving injection of a gas into the water body have traditionally been used for direct (in-situ) measurement of K_2 in a given reach. This paper shows how additional modelling of tracer test results can be used to quantify also hydrodynamic mechanisms (e.g. dispersion and storage exchange coefficients, etc.). Data from three tracer tests conducted in the River Lagan (Northern Ireland) using an inert gas (krypton, Kr) are re-analysed using two solute transport models (ADM, TSM) and an inverse-modelling framework (OTIS-P). Results for K_2 are consistent with previously published values for this reach (K_2 (20) ~10-40 d^{-1}). The storage area constituted 30-60% of the main cross-section area and the storage exchange rate was between 2.5×10^{-3}-$3.2\times10^{-3} s^{-1}$. The additional hydrodynamic parameters obtained give insight into transport and dispersion mechanisms within the reach.

Keywords: Modelling; River reaeration; Solute transport; Tracers; Transient storage

1.0 INTRODUCTION

The capacity of surface waters to assimilate oxygen-depleting contaminants (e.g. BOD pollution) depends critically on the oxygen (O_2) mass transfer (or reaeration) coefficient (K_2,) which characterises the rate of O_2 absorption across the air-water interface. Direct measurement in the field via dissolved gas tracer studies has proven the most reliable method to quantify K_2 (Reid et al., 2007). Hydrodynamic processes such as advection, dispersion, dilution (mixing) from groundwater base flow and exchange with storage zones affect also the spatial and temporal concentrations of non-volatile pollutants and tracers alike (Chin, 2006).

The direct tracer method for determining K_2 involves injecting (dissolving) in a stream body a non-volatile, conservative tracer (to assess physical advection, dispersion, and mixing effects) and a volatile, gas tracer (to assess additionally mass transfer across the air-water interface). The concentration-time curves (or *breakthrough curves*, BTCs) of the tracers at two predetermined downstream locations are then monitored. Conventionally, results from field tracer BTCs are interpreted first by normalising the concentration of the gas tracer to that of the conservative tracer (Kilpatrick *et al*., 1989). A first-order loss coefficient for the gas is then determined from logarithmic relations between concentration and travel times at the upstream and downstream sampling sites using either the normalised peak concentrations (*peak method*) or the total mass for the gas tracer calculated from the area under the BTC (*area method*) and the volumetric flow (Reid *et al*., 2007). The main drawback of these approaches is that although K_2 is quantified, the physical transport and dispersion parameters