A Large Scale Dye Tracing Experiment Measuring Times of Travel in the upper Yellow River, Baotou, Inner Mongolia, China

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Key Points:

- Acid red 52 was poured into upper Yellow River near Baotou city to determine the times of travel for a 170.6 km long reach.
- A three parameter lognormal distribution equation was used to fit the observed time concentration data.
- The travel times, mean velocities, and dispersion rates were calculated from the fitted probability density functions or curves.

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Abstract

To determine the times of travel within a 170.6 km long reach in the upper Yellow River, we carried out a dye experiment in May 2017. 48.75 kg of dye was poured simultaneously at 39 points on a floating bridge. Water samples at eight sites were collected at left bank flow, center flow, and right bank flow considering both the traffic convenience and the safety production. A Fluorometer 10-005 was used to measure the dye concentration in the water samples. A three-parameter lognormal distribution equation, where the logarithm is to the base e, was used to fit the observed time concentration data to establish the time-concentration response curve and to establish the probability density function. For a conservative tracer, the time concentration curve was generated by multiplying the fitted probability density function and its coefficient. The travel times of different parts of the dye plume for the seven sampling sites and mean velocities and longitudinal dispersion rates for five sub reaches were calculated. The mean velocities of centroid of dye plume ranged from 0.49 m s^{-1} to 0.69 m s^{-1} and the dispersion rates range from 0.13 m s^{-1} to 0.37 m s^{-1} for the discharge of 233 m^3 s^{-1} measured at the Baotou hydrometric station. Several empirical relations are given for attenuation of the peak probability density, passage time, travel times of leading-edge, travel times of centroid and travel times of trailing edge of the dye plume in the upper Yellow River, Baotou, Inner Mongolia, China.

Plain Language Summary

For a case of possible accidental pollution and spill in a river, it is necessary to know when and how long the downstream intakes should be closed. The scientists judge them by using the tools, including the time of travel, velocity, dispersion rate of the given contaminant, and water quality modeling. Generally, the knowledge of the time of travel, velocity, dispersion rates was obtained from some tracer experiments. And the water-quality model should be calibrated by the knowledge of times of travel and peak concentration. Before 2015, only two tracer experiments had been undertaken over the reaches from 2 km to 3.7 km in Yellow River. This article presents a large-scale dye experiment undertaken in 2017 extended over a reach of 170 km in the upper Yellow River. Background water samples at the pour site were collected in advance. A series of other water samples were collected at seven sites. The dye concentration in the supernatant was measured. The observed time concentration data were fitted by using a three-parameter lognormal probability density equation, where the logarithm is to the base e. From the functions, the travel times, mean velocities and dispersion rates of the dye plume were calculated.

1 Introduction

The Yellow River, located in the north of China, is the second largest river of China. The 5464-km-long waterway feeds about 12 percent of China's population, irrigates about 15 percent of arable land, supports 14 percent of national GDP and supplies water to more than 60 cities(ZX, 2019). Meanwhile, it accepts the waste water discharged from one thousand of point pollution sources(Zhang et al., 2011). It serves as a transportation corridor too. Hundreds of roads and railways cross on the main stream of the river. These point pollution sources and the complex infrastructure make the Yellow River vulnerable to accidental pollution and spills from various sources. For municipal water supply safety and effective emergency response, it is necessary to know the travel times, streamflow velocities, dispersion rates, and peak concentrations to the pollution and spill,which knowledge can be used to calibrate hydraulic and water-quality models. Yellow River is also well known as its concentration of suspended sediment. The historical record shows the maximum value is 69.6 kg m^{-3} at Toudaoguai station in the upper Yellow River, which occurred on July 27th, 1994. The concentration of suspended sediment in the Yellow River and the logistical difficulty and cost of the tracer experiments restricted the people's imaginary. Before 2015, only two tracer experiments had been undertaken over the reaches from 2 km to 3.7 km. In order to know whether the Acid Red 52 can be used as a tracer for the river or not, in October, 2015, first two experiments using Acid Red 52 conducted by us in a reach with length about 31 km near Baotou city in the Upper Yellow River. The experiment showed that Acid Red 52 can be selected as a tracer for the tracing experiment in the Yellow River. In order to obtain more accurate data about time of the travel and longitudinal dispersion rate for a longer reach and to understand the variations of the travel time and dispersion among several reaches, we carried out a large scale tracing experiment in the upper Yellow River in May, 2017. The study reach is between the Wangdahan floating bridge and Madihao irrigation pumping station (Figure 1). For the reach, the channel length is about 170.608 km and the straight-line length about 103.119 km, the sinuosity about 1.65 and average channel slope about 0.0125 percent. Two hydrometric stations are located near the two ends of the study reach. The Baotou station, established in January 2014, is located 6643 m upstream from the Wangdahan floating bridge. The Toudaoguai station, established in April 1958, is located 1108 m upstream from the Madihao irrigation pumping station. During the dye tracing experiment, the discharge was about 233 m^3 s^{-1} and the suspended sediment concentration was about 0.928 kg m^{-3} and the mean velocity measured by current meter was about 0.691 m s^{-1} at the Baotou station and 0.573 m s^{-1} at the Toudaoguai station. About 3.7 m^3 s^{-1} of wastewater was discharged into the reach between Baotou hydrometric station and the sampling site of Dengkou during the experiment.

2 Materials and Methods

2.1 Dye

Acid red 52 (Lot No. 170405, Purity 85%, Stength 551%) purchased from Jingzhou Arondyes Chemicals, Hubei, China was used to carry out the experiment of the times of travel.

2.2 Dye dissolution and release

For the discharge of 233 m^3 s^{-1}, 48.75 kg powder of acid red 52 was divided into 39 equal parts, 1.25 kg per part. Each part was put into a bucket respectively. The tap water was added into the 39 buckets. The mixture was stirred well to dissolve th powder fully at a factory. The dye solution was poured into Yellow River simultaneously and instantaneously, facing downstream, in only about the central 75 percent of the flow, at 06:50 on 26 May 2017 at 39 points from the Wangdahan floating bridge. Each pouring point was located at the approximate center of flow of each 39 equal discharge segment according to hydrometric specialist's experience.

2.3 Sample collection

Considering the work safety, water samples were collected at banks (0.5 m to 1.5 m from waters edge) and at center flow on bridges. A series of water samples at eight cross-sections of Wangdahan floating bridge (left bank flow, center flow, right bank flow), Tianjiayingzi (right bank flow), Dengkou (left bank flow), Dachengxi road bridge (left bank flow), Wujuniu floating bridge (center flow), Erdaohao floating bridge (center flow), Wuergeliang floating bridge (center flow) and Madihao pumping station (left bank flow) was collected and sealed into a glass bottle of 100 ml once at given intervals such as five minutes, ten minutes, fifteen minutes, twenty minutes, twenty-five minutes and thirty minutes. The water samples were sent to a laboratory for a static settlement in a water tank at least for 16 hours.

The average concentration in the water samples collected at Wangdahan floating bridge before dye pour was taken as background value.

2.4 Dye concentration measurement

Dye concentration was measured in a laboratory by a Turner Designs Fluorometer 10-005. The fluorometer was calibrated by a standard regent of 170 ppb, which was prepared by using deionized water to dissolve the powder of acid red 52. The concentration in the supernatant liquid after settlement was measured in a laboratory. The concentration corrected by the liquid temperature is reported according to the equation (1) (Smart & Laidlaw, 1977).

$$F = F_0 \exp\left(-0.029t\right) \tag{1}$$

where F is the fluorescence reading at temperature t and F_0 is the fluorescence at 0.

2.5 Observed time concentration curve fitting

(1) Subtracting background value from measured concentration. The background was about 0.287 ppb for the cross-section of Wangdahan floating bridge. Observed concentration was obtained by subtracting background value from the measured concentration.

(2) Fitted observed time-concentration response curve and fitted three parameters lognormal probability density function. The three-parameter log-normal equation (2), where the logarithm is to the base e, was used to fit the observed concentrations to establish a fitted time-concentration response curve:

$$C_r(i,t) = \frac{K_r}{\sqrt{2\pi}\sigma\left(t-t_0\right)} exp\left[-\frac{1}{2}\frac{\left[ln\left(t-t_0\right)-\mu\right]^2}{\sigma^2}\right] = K_r f\left(t\right) \tag{2}$$

where $C_r(i,t)$ = dye concentration, $\mu g L^{-1}$, at a cross-section i at time t; t = elapsed time after pour, h; t_0, μ, and σ are parameters, in which t_0 is the threshold (location) parameter of the lognormal random variable t. It is more convenient to use $\beta = exp(\mu)$ and $\omega = exp(\sigma^2)$ as the scale and shape parameters of the lognormal random variable t(Basak et al., 2009). K_r= fitted coefficient, $\mu g L^{-1} h$, which is related to the quantity of dye injected and flow discharge at sampling cross-section. $f(t)$ =three parameters lognormal probability density function, h^{-1}.

$$M_r = \int_{t_0}^{\infty} C_r(i,t)\mathrm{Qdt} = \mathrm{Q}\int_{t_0}^{\infty} C_r(i,t)\mathrm{dt} = K_r Q \tag{3}$$

For a conservative dye,

$$K_i = \frac{M_i \times 10^9}{Q \times 1000 \times 3600} \tag{4}$$

where Q= discharge at sampling cross-section, $m^3 s^{-1}$; M_r= the mass of tracer to pass a cross section, kg; M_i= total quantity of dye poured, kg; K_i= calculated coefficient using the quantity of dye poured and flow discharge at sampling cross-section, $\mu g L^{-1} h$.

(3) Recovery ratio(Jobson, 1997). The percentage recovery was computed by using the fitted coefficeint K_r of the time-concentration response curve as

$$\mathrm{R_r} = \frac{K_r}{K_i} = \frac{M_r}{M_i} \tag{5}$$

where R_r = percentage recovery; K_r, K_i , M_r and M_i are defined as above.

(4) Conservative time-concentration curve. The fitted time-concentration curves were adjusted to the conservative time-concentration response curve, as follows:

$$C(i,t) = K_i f\left(t\right) \tag{6}$$

Where $C(i,t)$, K_i and $f(t)$ are defined as above.

2.6 Travel time and dispersion rate

Dispersion time can be obtained from the fitted three parameter lognormal distribution density function. As defined in a USGS paper (Kilpatrick, 1993), the dye concentration and movement characteristics pertinent to time-of-travel measurements include: T_L= travel time of leading edge of dye plume, h. In this paper, t_0 defined in equation (2) substitute for T_L; T_p = travel time of peak concentration of dye plume, h; $T_{_{10pt}}$ = travel time of trailing edge of dye plume where dye concentration is reduced to 10 percent of the peak concentration, h; T_t = travel time of trailing edge of dye plume, h; and T_c = travel time of centroid of dye plume, h. $T_{_{10pt}}$ can be found from the time-concentration response curves. The travel time of centroid and the travel time of peak concentration of dye plume can be computed by using equation (7) and equation (8) (Sangal & Biswas, 1970; Smith & Merceret, 2000; Aristizabal, 2012).

$$T_c = t_0 + \exp(\mu + \frac{\sigma^2}{2}) \tag{7}$$

$$T_\mathrm{p} = t_0 + \exp(\mu - \sigma^2) \tag{8}$$

where T_0, μ, and σ are the parameters of the three-parameter log-normal equation (2). The mean travel time for the flow along a streamline is the difference in elapsed time of the centroid of the time-concentration curves defined upstream and downstream on the same streamline:

$$t_c = T_{c(n+1)} - T_{c(n)} \tag{9}$$

where n is the number of the sampling site. Similarly, the travel times of the leading edge, peak concentration, and trailing edge along a given streamline are, respectively,

$$t_L = T_{L(n+1)} - T_{L(n)} \tag{10}$$

$$t_p = T_{p(n+1)} - T_{p(n)} \tag{11}$$

and

$$t_t = T_{t(n+1)} - T_{t(n)} \tag{12}$$

where all terms are as previously defined. These travel times are used to calculate the mean velocity of the travel-time components through a subreach. These mean velocities are used to estimate longitudinal dispersion rates and also are used for management decisions for source-water intakes when a contaminant is present in the river (Mccarthy, 2009; Whiteman, 2012). The time, T_d, necessary for the response to pass a sampling site is

$$T_d = T_{t(n)} - T_{L(n)} \tag{13}$$

For a subreach, the longitudinal dispersion rate R_d was estimated by subtracting the velocity of the trailing edge of the dye plume from the velocity of the leading edge of the dye plume.

$$R_d = \frac{L}{3600t_L} - \frac{L}{3600t_t} \tag{14}$$

where R_d = dispersion rate, ms^{-1}; L = channel length of a subreach, m; t_L = travel time of the leading edge along a given streamline, h, and t_t= travel time of trailing edge along the streamline, h. Due to longitudinal dispersion continues indefinitely, the travel time of trailing edge was defined as the time, in hours, from the pour until the dye concentration at the sampling cross section was reduced to 0.1 times or 0.05 times the peak(Jobson, 1996). In this paper, T_{10pt} and T_t determined from time-concentration curve(Mccarthy, 2009; Whiteman, 2012), $T_{0.99995}$ and $T_{0.95}$ calculated by using the fitted parameters of $f(t)$ in equation (2) for the $99.995th$ percentile and $95th$ percentile were taken as the travel times of trailing edge,too. $T_{0.99995}$ and $T_{0.95}$ were calculated by using equation (15) and equation (16).

$$T_{0.95} = T_0 + \exp(\mu + 1.645\sigma) \tag{15}$$

$$T_{0.99995} = T_0 + \exp(\mu + 3.9\sigma) \tag{16}$$

3 Data

3.1 Travel times

All the observed data were used to fit the time concentration curves for seven sampling sites of Tianjiayingzi, Dengkou, Dachengxi road bridge, Wujuniu floating bridge, Erdaohao floating bridge, Wuergeliang floating bridge and Madihao pumping station. The fitted parameters for time-concnetration curves are given in Table 1 and the time concentration curves were given in Figure 2. From Table 1 and Figure 2, it can be seen that there were missing data for the long tail of the dye plume at sampling sites of Tianjiayingzi and Dachengxi road bridge, and the recovery ratio was high at Erdaohao floating bridge, which would cause an inconsistency in dealing with long tail of the dye plume between the three sites and the other sampling sites. So the partial tail of the curves at the three sites should be rejected when calculating the time and velocity of the traling edge.

The travel times of the leading edge, peak concentration, centroid, trailing edge at 10 percent of the peak concentration, T_t determined from the fitted time-concentration curve, 99.995th percentile trailing edge, 95th percentile trailing edge of the dye plume, time for dye plume to pass site and peak value of the fitted three parameter lognormal probability density are given in Table 2 for seven sampling sites.

3.1.1 Attenuation of peak Value of lognormal probability density

Figure 3 is a plot of the peak value of fitted lognormal probability density (LPD_p) as a function of elapsed time (T_p) to the peak of all the data. The regression equation based on travel time that best fit all the data was

$$LPD_p = 3.57601 \times {T_p}^{-0.86386} \tag{17}$$

This equation predicted the seven data points with a residual sum of squares of 4.82509×10^{-4}. The R-Square(COD) was 0.99994, and the Adj. R-Square was 0.99992.

3.1.2 Time of Passage of Pollutant

Figure 4 is a plot of time for dye plume to pass site (T_{10d}) as a function of the peak value of fitted lognormal probability density (LPD_p) of all the data. The regression equation based on LPD_p that best fit all the data was

$$T_{10d} = 2.24366 \times {LPD_p}^{-0.96315} \tag{18}$$

This equation predicted the seven data points with a residual sum of squares of 1.67388. The R-Square(COD) was 0.99524, and the Adj. R-Square was 0.99429.

Figure 5 is a plot of time for dye plume to pass site (T_{10d}) as a function of elapsed time (T_p) to the peak of all the data. The regression equation based on travel time that best fit all the data was

$$T_{10d} = 0.68738 \times {T_p}^{0.81403} \tag{19}$$

This equation predicted the seven data points with a residual sum of squares of 0.97973. The R-Square(COD) was 0.99721, and the Adj. R-Square was 0.99666. The relation between travel time of the peak concentration and duration determined from this study closely resembles the relation determined by Kilpatrick and Wilson (Kilpatrick & J.F. Wilson, 1989).

3.1.3 Time of Travel of Leading Edge

Figure 6 is a plot of time of travel of leading edge (T_L) as a function of elapsed time (T_p) to the peak of all the data. The regression equation based on travel time that best fit all the data was

$$T_L = -0.78576 + 0.90399 \times T_p \tag{20}$$

This equation predicted the seven data points with a residual sum of squares of 7.24789. The R-Square(COD) was 0.99771, and the Adj. R-Square was 0.99725.

3.1.4 Time of Travel of Centroid

Figure 7 is a plot of time of travel of Centriod (T_c) as a function of elapsed time (T_p) to the peak of all the data. The regression equation based on travel time that best fit all the data was

$$T_c = 0.00649 + 1.0522 \times T_p \tag{21}$$

This equation predicted the seven data points with a residual sum of squares of 1.56994. The R-Square(COD) was 0.99963, and the Adj. R-Square was 0.99956.

3.1.5 Time of Travel of Tailing Edge

Figure 8 is a plot of time of travel of trailing edge (T_t) as a function of elapsed time (T_p) to the peak of all the data. The regression equation based on travel time that best fit all the data was

$$T_t = 0.56853 + 1.20406 \times T_p \tag{22}$$

This equation predicted the seven data points with a residual sum of squares of 5.88722. The R-Square(COD) was 0.99895, and the Adj. R-Square was 0.99874.

3.2 Mean velocities and longitudinal dispersion rates

Mean velocities between sampling sites were calculated for threshold parameter of the three parameter lognormal probability density functions, the leading edge, peak concentration, centroid, trailing edge at 10 percent of the peak concentration, T_t determined from the time-concentration curve, 99. 995th percentile trailing edge, 95th percentile trailing edge of the dye plume and longitudinal dispersion rate are given in Table 3 for five sub reaches. The dispersion rates were estimated by subtracting the velocity of the $95th$ percentile trailing edge of the dye plume from the velocity of the leading edge for the fitted threshold parameter t_0. For a sub reach, the mean velocity for the centroid of the dye plume most accurately represents the streamflow velocity, whereas the velocities of the other portions of the dye plume suggest the possible rates of the dispersion of contaminants spilled into the study reach(Mccarthy, 2009; Whiteman, 2012).

For the dye tracing experiments, when the discharge was about 233 m^3 s^{-1} at Baotou hydrometry station, the mean velocities of the leading edge of the dye plume ranged from 0.51 m s^{-1} to 0.9 m s^{-1} for the five subreaches. The velocities of the peak concentration of the dye plume ranged from 0.55 m s^{-1} to 0.77 m s^{-1}. The velocities of the centroid of the dye plume ranged from 0.49 m s^{-1} to 0.69 m s^{-1}. The velocity of the trailing edge at 10 percent of the peak concentration of the dye plume ranged from 0.41 m s^{-1} to 0.58 m s^{-1}. The mean longitudinal dispersion rates ranged from 0.13 m s^{-1} to 0.37 m s^{-1}.

4 Conclusions

Though the suspended sediment concentration was about 0.928 kg m^{-3}, the acid red 52 could be used in the large-scale tracer experiment in the upper Yellow River. The three parameter lognormal distribution equation, where the logarithm is to the base e, was used to fit the observed time concentration data at seven sampling sites to establish seven time-concentration response curves and to establish the probability density function. The probability density equation fitted the data well, except the long tail with concentration fluctuation of the time-concentration response curve.

Based on the fitted time concentration curves and fitted three parameter lognormal probability density functions, the times of travel, passage times, mean velocities of the dye plume at seven sampling sites were calculated. Then the ones for some subreaches were calculated. Finally, the longitudinal dispersion rates for some subreaches were calculated.

Both the Baotou hydrometric station and Toudaoguai hydrometric station, which are at the head and end of the study reach, are located at the head of a long uniform reach with comparative stable banks and on the outer bank downstream from the bend. Generally peaking, the mean flow velocities at the two stations cannot represent the mean flow velocities of the seven subreaches accurately. Among the seven subreaches, only the subreach between Wangdahan road floating bridge and the Tianjiayingzi has the same mean flow velocity as the Baotou hydrometric station.

In this paper, several empirical relations are given for attenuation of peak value of lognormal probability density, passage time (duration) of the dye plume, times of travel of leading edge of the dye plume, travel times of the peak concentration, times of travel of centroid and times of travel of trailing edge of the dye plume in the upper Yellow River, Baotou, Inner Mongolia, China. The regression equations best fit all the data. All the R-Square(COD) is greater than 0.995. However, these relations are not recommended as a substitute for field studies for other stream flows, especially for extreme low and high flows. The corresponding dye experiments should be conducted for in order to supply more accurate travel time estimates.

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The dataset compiled by us has been upload to ScienceDB(Sun, 2020), which contains the observed time concentration data and fitted curves. Protection was set by us for 12 months. After this paper is accepted, we will add the journal to the dataset and apply to the ScienceDB for its opening.

References

Aristizabal, R. J. (2012). *Estimating the parameters of the three-parameter lognormal distribution* (Theses and Dissertations, Florida International University). `https://digitalcommons.fiu.edu/etd/575/`. (Accessed on 2020-03-23)

Basak, P., Basak, I., & Balakrishnan, N. (2009). Estimation for the three-parameter lognormal distribution based on progressively censored data. *Computational Statistics & Data Analysis*, *53*(10), 3580-3592. doi: 10.1016/j.csda.2009.03.015

Jobson, H. E. (1996). *Prediction of traveltime and longitudinal dispersion in rivers and streams* (report No. Water-Resources Investigations Report 96-4013). Reston, VA: U.S. Geological Survey. `https://pubs.usgs.gov/wri/1996/4013/documents/dispersion.pdf`. (Accessed on 2020-03-20) doi: 10.3133/wri964013

Jobson, H. E. (1997). Predicting travel time and dispersion in rivers and streams. *Journal of Hydraulic Engineering*, *123*(11), 971-978.

Kilpatrick, F. (1993). *Simulation of soluble waste transport and buildup in surface waters using tracers* (report No. Techniques of Water-Resources Investigations 03-A20). U.S. Geological Survey. `http://pubs.usgs.gov/twri/twri3-a20/html/pdf.html`. (Accessed on 2016-07-14) doi: 10.3133/twri03A20

Kilpatrick, F., & J.F. Wilson, J. (1989). *Measurement of time of travel in streams by dye tracing* (report No. Techniques of Water-Resources Investigations 3-A9). U.S. Geological Survey. `https://pubs.usgs.gov/twri/twri3-a9/html/pdf.html`. (Accessed on 2020-04-08)

Mccarthy, P. M. (2009). *Travel times, streamflow velocities, and dispersion rates in the yellowstone river, montana* (report No. Scientific Investigations Re-

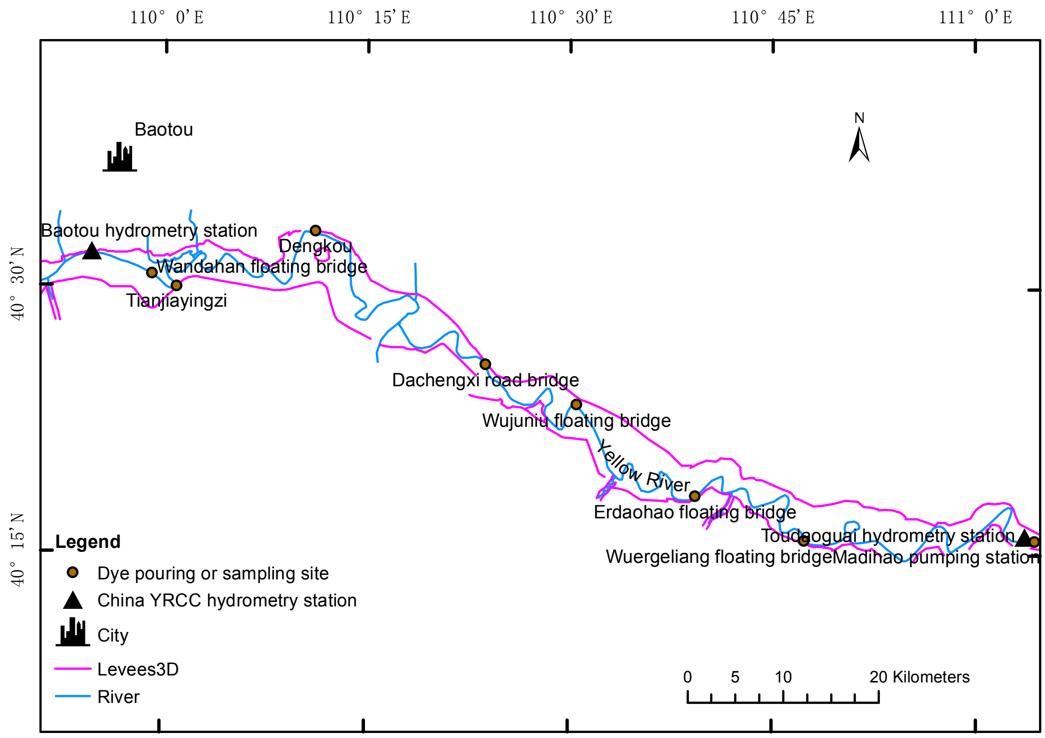


Figure 1. Location of sites used for dye pouring and sampling along the study area, upper Yellow River, Baotou, Inner Mongolia, China

port 2009-5261). U.S. Geological Survey. `http://pubs.usgs.gov/sir/2009/5261/downloads/sir2009-5261.pdf`. (Accessed on 2016-07-11) doi: 10.3133/sir20095261

Sangal, B., & Biswas, A. (1970, 04). The 3-parameter log normal distribution and its applications in hydrology. *Water Resources Research - WATER RESOUR RES*, *6*, 505-515. doi: 10.1029/WR006i002p00505

Smart, P., & Laidlaw, I. (1977, 02). An evaluation of some fluorescent dyes for water tracing. *Water Resources Research - WATER RESOUR RES*, *13*, 15-33. doi: 10.1029/WR013i001p00015

Smith, B., & Merceret, F. (2000, 09). The lognormal distribution. *The College Mathematics Journal*, *31*, 259. doi: 10.2307/2687413

Sun, Z.-d. (2020). *Data from:tracing experiment in the inner mongolia reach of the upper yellow river.* Science Data Bank. Retrieved from `http://www.sciencedb.cn/project/data/699703196448194560` doi: doi:10.11922/sciencedb.00057

Whiteman, A. (2012). *Travel times, streamflow velocities, and dispersion rates in the missouri river upstream from canyon ferry lake, montana* (report No. Scientific Investigations Report 2012-5044). Reston, VA: U.S. Geological Survey. `http://pubs.usgs.gov/sir/2012/5044/SIR2012-5044.pdf`. (Accessed on 2016-07-11) doi: 10.3133/sir20125044

Zhang, S.-k., Huang, J.-h., Yang, Y.-c., Peng, B., Liu, H., & Tian, Y.-l. (2011). Survey and analysis of pollution sources in yellow river basin (in chinese). *Yellow River*, *33*(12), 45-47.

ZX (Ed.). (2019). *China focus: The yellow river, mother river of chinese nation* [news]. `http://www.xinhuanet.com/english/2019-09/20/c_138408423.htm`. (Accessed on 2020-03-19)

Table 1. Fitted coefficents and parameters

Site name	Site type	River meters downstream from dye pour	Background concentration ($\mu g l^{-1}$)	K_r	t_0	σ	μ	Recovery ratio (%)
Wangdahanfloatingbridge	Dye pour	0	0.287					
Tianjiayingzi	Sampling	3212.3	0.287	50.53174	0.99297	0.63371	-1.41093	103.9
Dengkou	Sampling	31496.2	0.287	45.47476	10.48247	0.45739	0.88315	93.5
Dachengxiroadbridge	Sampling	68465.9	0.253	49.04638	24.44559	0.52921	1.51688	100.9
Wujuniufloatingbridge	Sampling	86671.4	0	50.43782	30.61766	0.44659	1.70448	103.7
Erdaohaofloatingbridge	Sampling	110431.8	0.095	53.49571	40.29790	0.51202	1.93061	110.0
Wuergeliangfloatingbridge	Sampling	131375.2	0.101	49.81915	47.56855	0.37764	2.23170	102.4
Madihaofloatingbridge	Sampling	170608.4	0.212	49.22915	68.98656	0.60019	2.20946	101.2

Table 2. Travel times for upper Yellow River, Baotou, Inner Mongolia, China

Site name	Leading edge, T_L	Peak concentration, T_p	Centroid T_c	Trailing edge at 10 percent peak concen tration T_{10p}	Trailing edge T_t	$99.995th$ percentile trailing edge $T_{0.99995}$	$95th$ percentile trailling edge, $T_{0.95}$	Time for dye plume to pass site (h), T_{10d}	Peak value of probability den sity $f(t)$
$Wandahanfloatingbridge$	0	0	0	0	0	0	0		
$Tianjiayingzi$	1.00	1.16	1.29	1.63	4.01	3.88	1.68	0.64	3.1549
$Dengkou$	10.78	12.44	13.17	15.72	22.99	24.88	15.61	5.24	0.4004
$Dachengxiroadbridge$	24.88	27.89	29.69	35.17	51.40	60.35	35.33	10.72	0.1902
$Wujuniufloatingbridge$	31.37	35.12	36.69	42.36	56.03	62.00	42.08	11.74	0.1795
$Erdaohaofloatingbridge$	41.00	45.60	48.16	56.21	77.52	91.08	56.30	15.91	0.1289
$Wuergeliangfloatingbridge$	49.51	55.65	57.57	65.73	81.11	88.20	64.91	18.16	0.1218
$Madihaopumpingstation$	69.64	75.34	79.90	92.03	126.77	163.64	93.44	23.04	0.0874

Table 3. Mean streamflow velocities and logitudinal dispersion rates

Site name	Threshold parameter t_0	Leading edge	Peak concentration	Centroid	Trailing edge at 10 percent peak concentration	Trailing edge	$99.995th$ percentile trailing edge	$95th$ percentile trailing edge	Longitudinal dispersion rate
Wandahan									
Tianjiayingzi	0.899	0.891	0.772	0.691	0.548	0.223	0.230	0.530	0.369
Dengkou	0.828	0.804	0.696	0.662	0.558	0.414	0.374	0.564	0.264
Wujuniu	0.761	0.744	0.676	0.651	0.575	0.464	0.413	0.579	0.182
Wuergeliang	0.733	0.685	0.605	0.595	0.531	0.495	0.474	0.544	0.189
Madihao	0.509	0.541	0.553	0.488	0.414	0.239	0.144	0.382	0.127

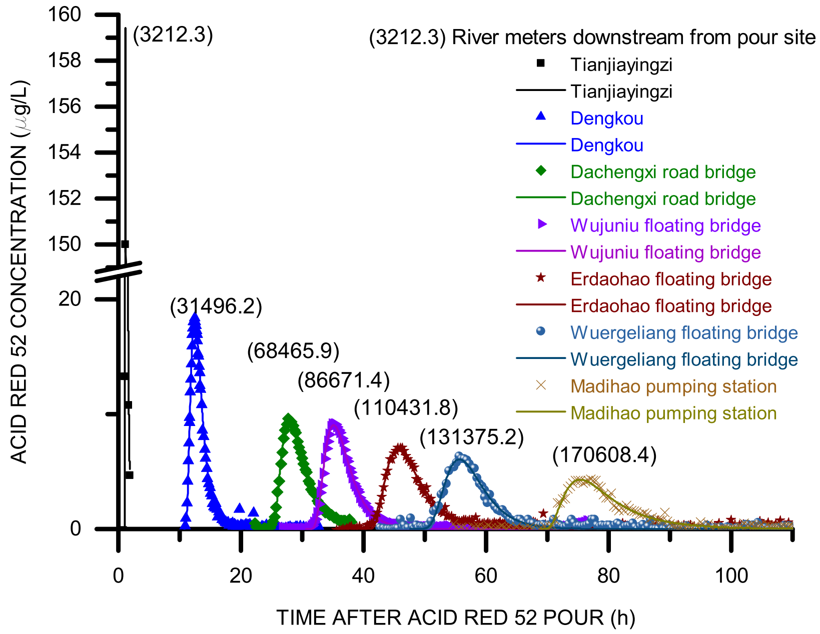


Figure 2. Observed time-concentration data and fitted time-concentration curves

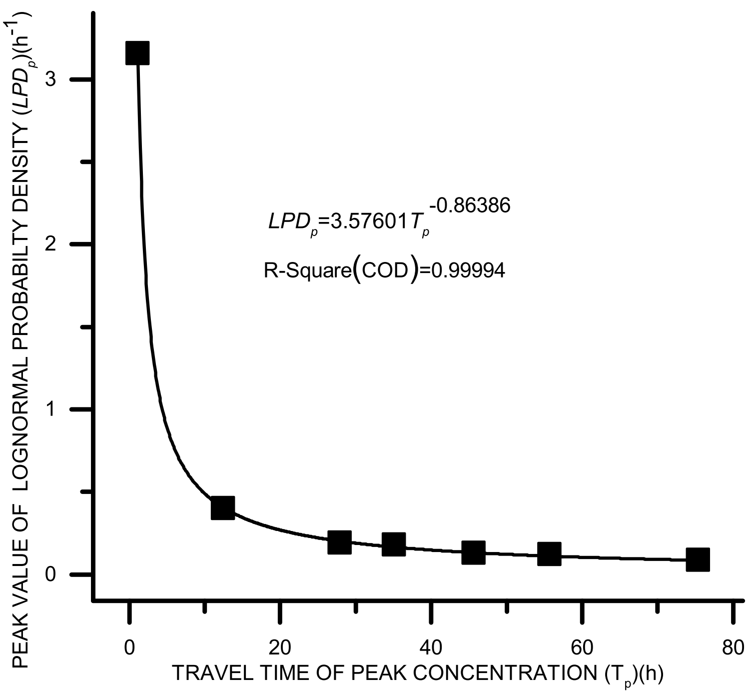


Figure 3. Attenuation of Peak Value of lognormal probability density

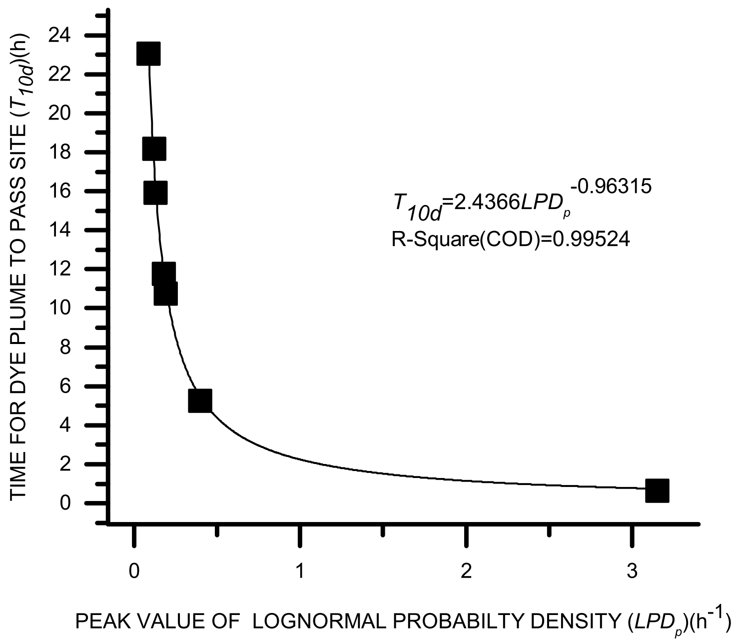


Figure 4. Relation between peak values of lognormal probability density and passage times (duration) of the dye plume in the upper Yellow River, Baotou, Inner Mongolia, China.

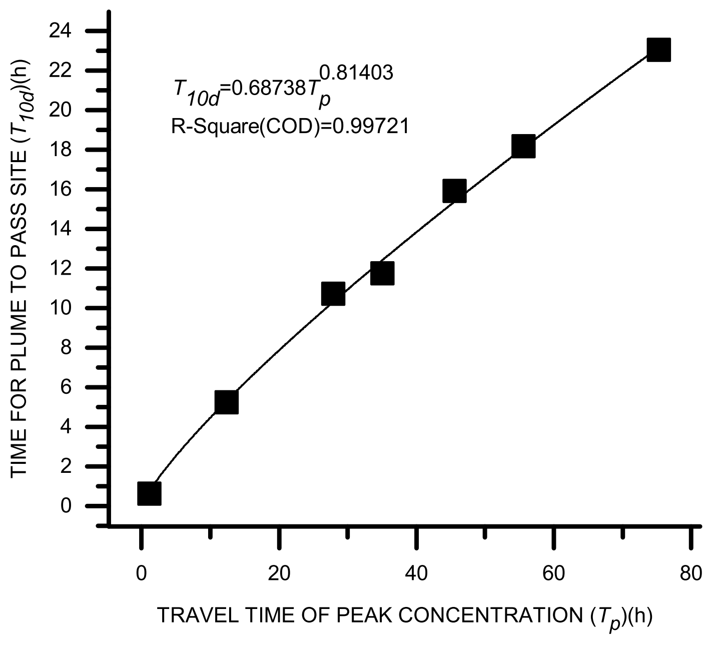


Figure 5. Relation between travel times of the peak concentration and passage times (duration) of the dye plume in the upper Yellow River, Baotou, Inner Mongolia, China.

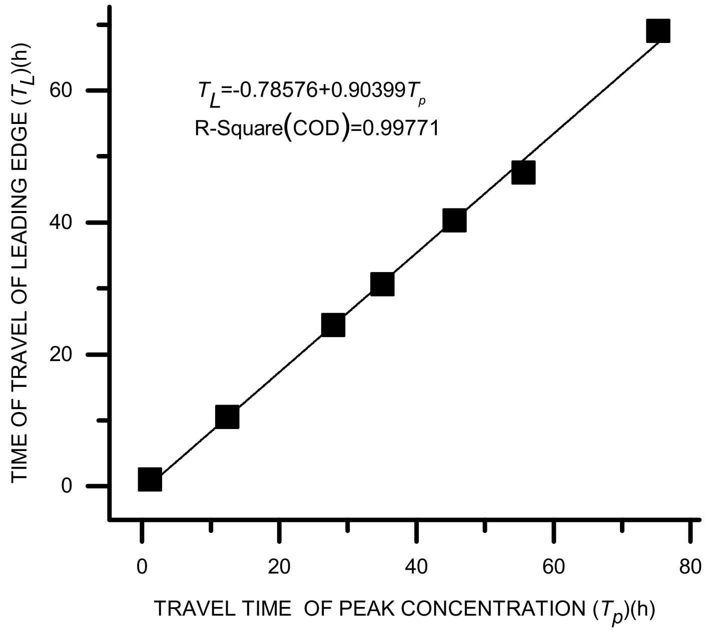


Figure 6. Relation between travel times of the peak concentration and times of travel of leading edge of the dye plume in the upper Yellow River, Baotou, Inner Mongolia, China.

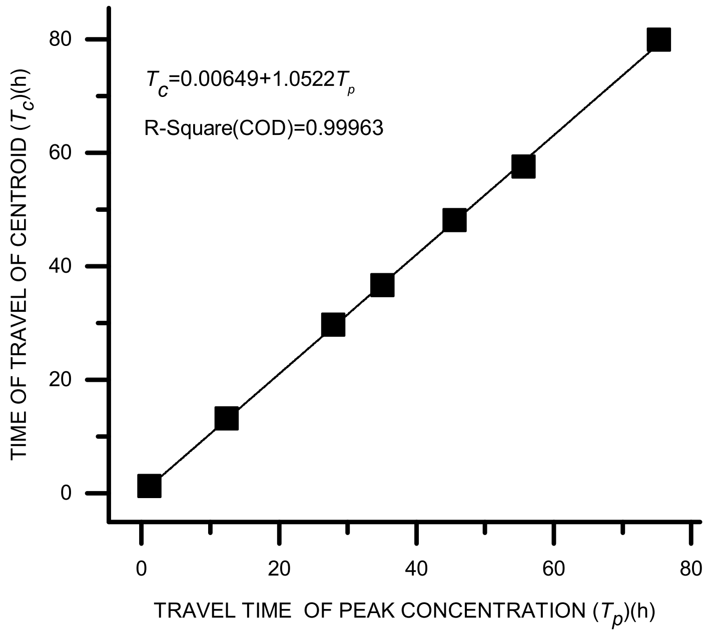


Figure 7. Relation between travel times of the peak concentration and times of travel of centriod of the dye plume in the upper Yellow River, Baotou, Inner Mongolia, China.

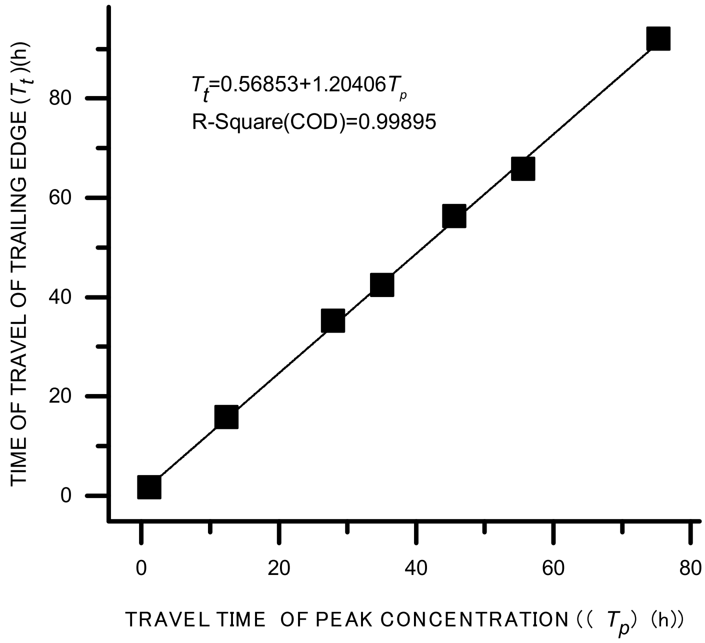
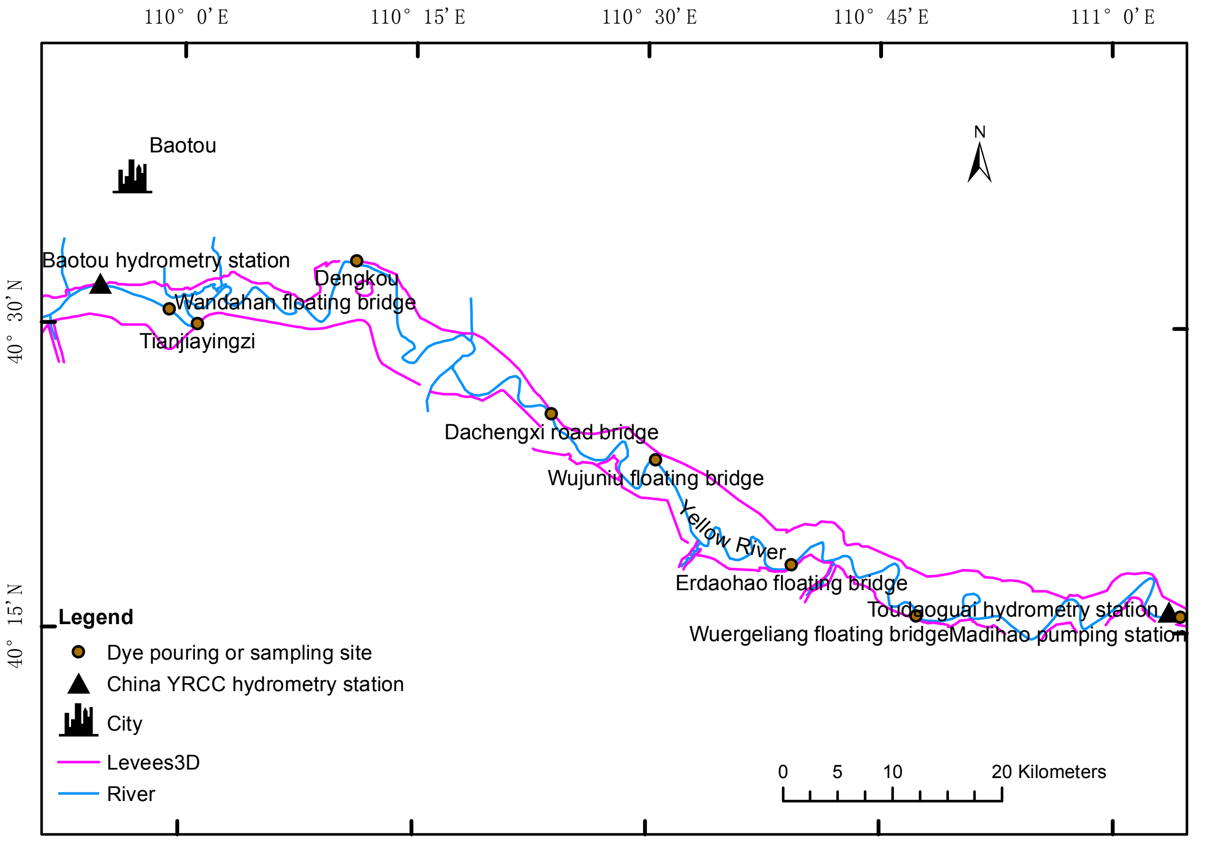


Figure 8. Relation between travel times of the peak concentration and times of travel of trailing edge of the dye plume in the upper Yellow River, Baotou, Inner Mongolia, China.

Figure 1.



110° 0'E
110° 15'E
110° 30'E
110° 45'E
111° 0'E
40° 30'N
40° 15'N
N
Baotou
Baotou hydrometry station
Dengkou
Wandahan floating bridge
Tianjiayingzi
Dachengxi road bridge
Wujuniu floating bridge
Yellow River
Erdaohao floating bridge
Toudaoguai hydrometry station
Wuergeliang floating bridge
Madihao pumping station
Legend
Dye pouring or sampling site
China YRCC hydrometry station
City
Levees3D
River
0
5
10
20 Kilometers

Figure 2.

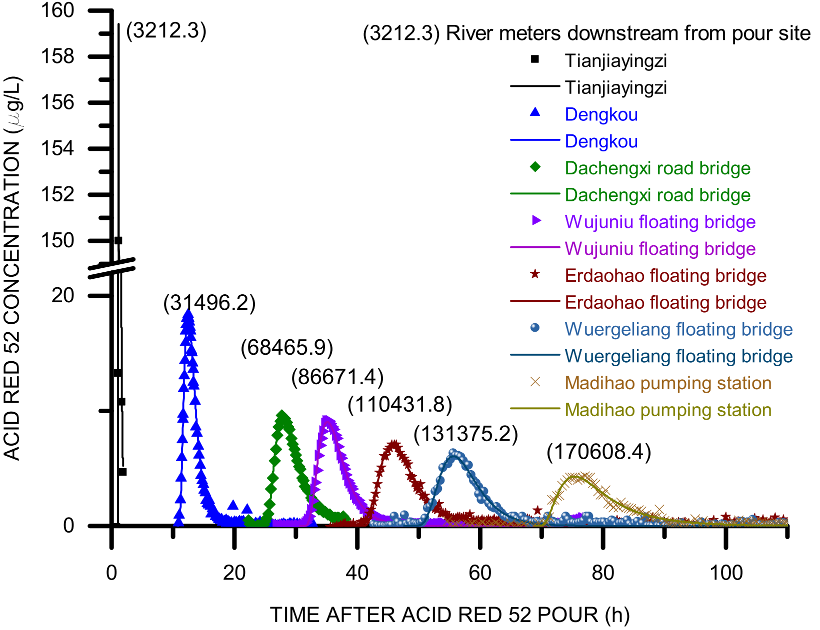
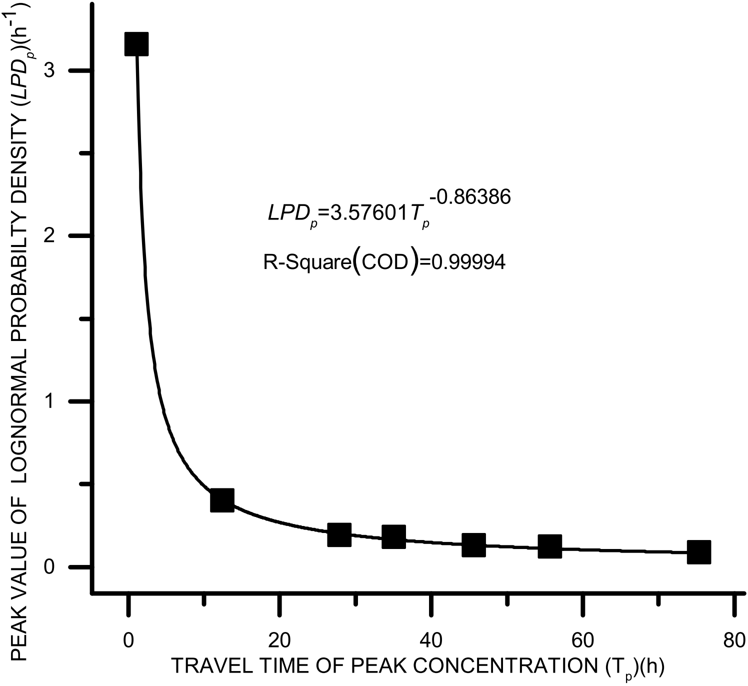
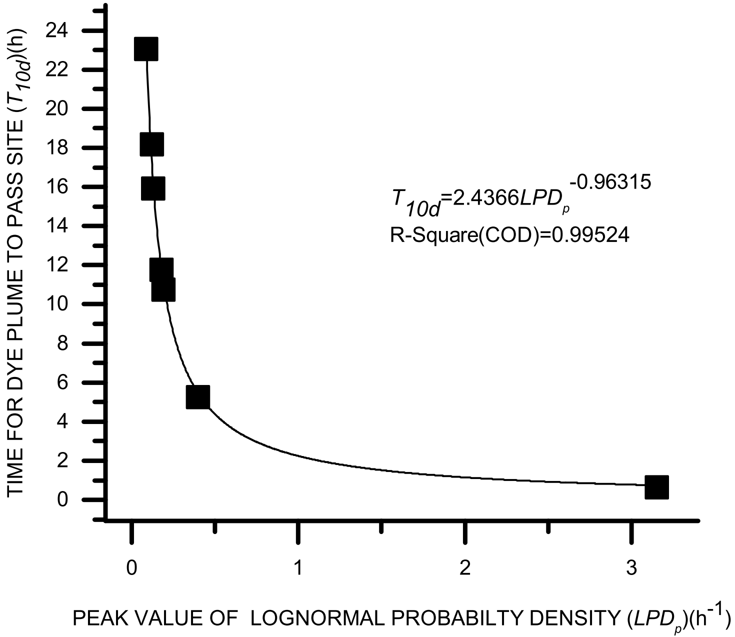

(3212.3) River meters downstream from pour site
Tianjiayingzi
Tianjiayingzi
Dengkou
Dengkou
Dachengxi road bridge
Dachengxi road bridge
Wujuniu floating bridge
Wujuniu floating bridge
Erdaohao floating bridge
Erdaohao floating bridge
Wuergeliang floating bridge
Wuergeliang floating bridge
Madihao pumping station
Madihao pumping station
(3212.3)
(31496.2)
(68465.9)
(86671.4)
(110431.8)
(131375.2)
(170608.4)
ACID RED 52 CONCENTRATION (μg/L)
TIME AFTER ACID RED 52 POUR (h)
160
158
156
154
152
150
20
0
0
20
40
60
80
100

Figure 3.



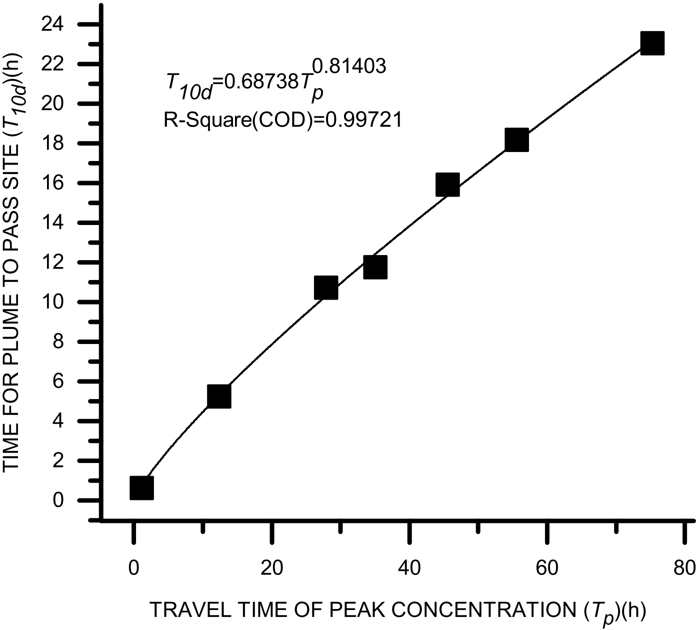
PEAK VALUE OF LOGNORMAL PROBABILTY DENSITY (LPDp)(h-1)
3
2
1
0
LPDp=3.57601Tp-0.86386
R-Square(COD)=0.99994
0
20
40
60
80
TRAVEL TIME OF PEAK CONCENTRATION (Tp)(h)

Figure 4.



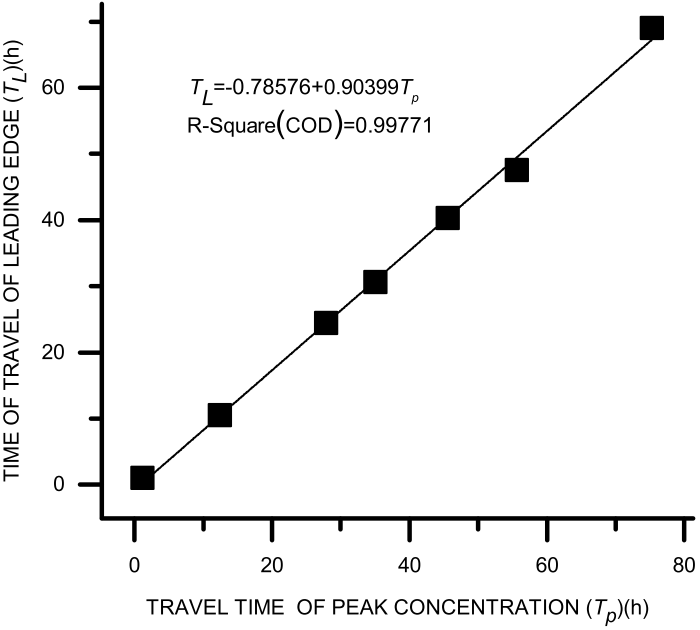
TIME FOR DYE PLUME TO PASS SITE (T_{10d})(h)
24
22
20
18
16
14
12
10
8
6
4
2
0
0
1
2
3
T_{10d}=2.4366$LPD_p^{-0.96315}$
R-Square(COD)=0.99524
PEAK VALUE OF LOGNORMAL PROBABILTY DENSITY (LPD_p)(h^{-1})

Figure 5.



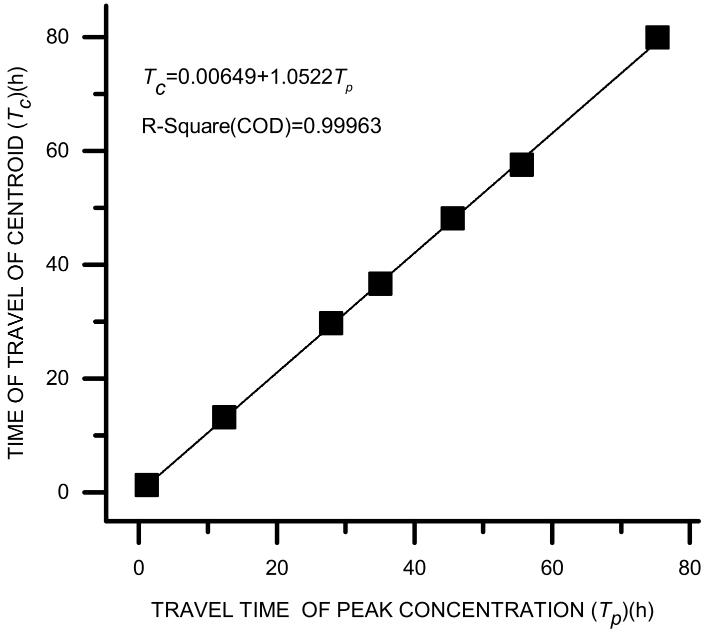
T_{10d}=0.68738$T_p^{0.81403}$
R-Square(COD)=0.99721
TIME FOR PLUME TO PASS SITE (T_{10d})(h)
24
22
20
18
16
14
12
10
8
6
4
2
0
0
20
40
60
80
TRAVEL TIME OF PEAK CONCENTRATION (T_p)(h)

Figure 6.



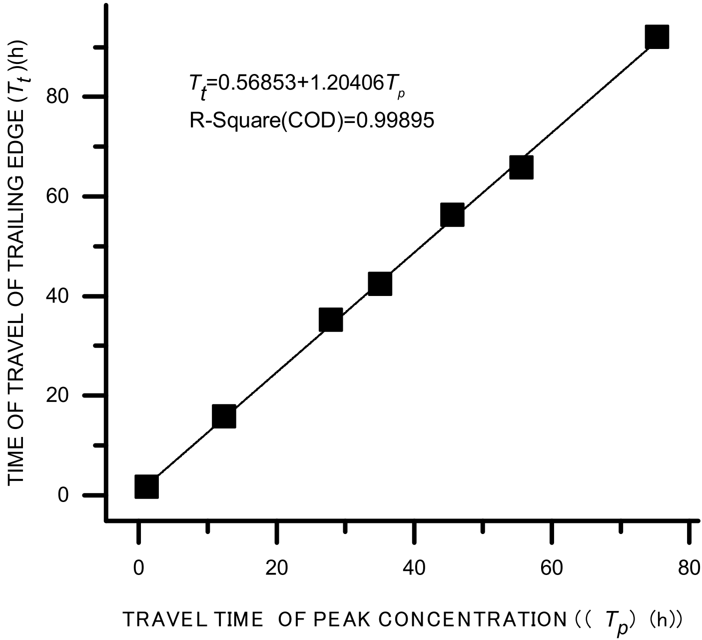
T_L=-0.78576+0.90399T_p
R-Square(COD)=0.99771
TIME OF TRAVEL OF LEADING EDGE (T_L)(h)
0
20
40
60
0
20
40
60
80
TRAVEL TIME OF PEAK CONCENTRATION (T_p)(h)

Figure 7.



T_c=0.00649+1.0522T_p
R-Square(COD)=0.99963
TIME OF TRAVEL OF CENTROID (T_c)(h)
TRAVEL TIME OF PEAK CONCENTRATION (T_p)(h)
0
20
40
60
80
0
20
40
60
80

Figure 8.



T_t=0.56853+1.20406T_p
R-Square(COD)=0.99895
TIME OF TRAVEL OF TRAILING EDGE (T_t)(h)
0
20
40
60
80
0
20
40
60
80
TRAVEL TIME OF PEAK CONCENTRATION ((T_p) (h))