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Joint Nuclear Research Centre
Ispra Establishment — Italy

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Abstract

In this paper a method is presented to evaluate the mean residence time of water in a monomictic lake.

A certain knowledge, concerning the hydrologic cycle and the time evolution of the thermocline of the lake to be treated, is assumed.

A computer code has been established to serve the purpose and some examples have been calculated.

§ 1. Introduction

In the general case of a monomictic lake, i.e. a lake which has a water turnover, whether partial or total, only once a year, the evaluation of the mean residence time of the water in the lake proceeds as follows (ref. 1,2).

We define an annual hydrologic cycle of the lake with a partial water turnover, which we will refer to as a partial cycle.

We further have a pluriannual cycle, composed of N partial cycles (occasionally N might be equal to zero) and one cycle with a complete water turnover, which will be called a total cycle. Every cycle is divided into intervals of constant epilimnion volume. The subdivision into intervals is based upon a statistical knowledge of the time evolution of the thermocline in the lake during the year. The last interval of every cycle represents the condition of greatest homogeneity (occasionally total homogeneity) of the lake, while the first interval of every cycle is that of transition between the turnover and the stratification period.

The calculation gives, at the end of a partial cycle, a dilution coefficient for the original water in the epilimnion called α_{ep}, so that after N identical partial cycles the dilution coefficient for the original water in the epilimnion becomes α_{ep}^N.

The total cycle, appearing after N partial cycles, gives the dilution coefficient α for the whole lake.

If the pluriannual cycle is composed of N+1 = T annual cycles, the mean residence time τ of the water in the lake is obtained by means of the following relationships.

$$\tau = (1-\alpha)\frac{T}{2} + (1-\alpha)\alpha\frac{3}{2}T + (1-\alpha)\alpha^2\frac{5}{2}T + \text{------}$$

$$+ (1-\alpha)\alpha^N \frac{2N+1}{2} T + \text{-----}$$

$$\tau = (1-\alpha)\frac{T}{2}\left\{1 + 3\alpha + 5\alpha^2 + \ldots + (2N+1)\alpha^N + \ldots\right\}$$

$$= (1-\alpha)\frac{T}{2}\sum_{N=0}^{\infty}(2N+1)\alpha^N$$

$$= (1-\alpha)\frac{T}{2}\left\{\sum_{N=0}^{\infty}2N\alpha^N + \sum_{N=0}^{\infty}\alpha^N\right\}$$

$$= (1-\alpha)\frac{T}{2}\left\{2\sum_{N=0}^{\infty}N\alpha^N + \frac{1}{1-\alpha}\right\}$$

where

$$\sum_{N=0}^{\infty}N\alpha^N = \alpha\sum_{N=0}^{\infty}N\alpha^{N-1}$$

$$= \alpha\sum N\frac{d}{d\alpha}\alpha^N.$$

$$= \alpha\frac{d}{d\alpha}\frac{1}{1-\alpha}$$

$$= \alpha\frac{1}{(1-\alpha)^2}$$

we therefore obtain

$$\tau = (1-\alpha)\frac{T}{2}\left\{2\alpha\frac{1}{(1-\alpha)^2} + \frac{1}{1-\alpha}\right\}$$

$$= \frac{T}{2}\left\{\frac{2\alpha}{1-\alpha} + 1\right\}$$

$$= \frac{T}{2}\,\frac{2\alpha + 1 - \alpha}{1-\alpha} = \frac{T}{2}\,\frac{1+\alpha}{1-\alpha}$$

The calculation of α_{ep} (or α) is based upon the general assumption that the mixing of inflowing waters with the original lake water is limited to the region above the thermocline, or epilimnion.

The volume of the original water in the epilimnion at the end of interval i is determined by the equation

$$\Omega'_i\ (t) = -\frac{1}{\beta_i}\,\Omega_i\ (t) \tag{1}$$

where $\frac{1}{\beta_i}$ is the probability that a water volume element, present somewhere in the lake at the beginning of time interval i, flows out of the lake during the same interval.

We obtain

$$\Omega_i = \Omega_{oi}\ \exp\left(-\frac{t}{\beta_i}\right) \tag{2}$$

where Ω_{oi} is the volume of the original water in the epilimnion at the beginning of the interval i.

If we define a retention coefficient

$$\varrho_i = \frac{V^i_{ep}}{V^i_{ep} + q_i\,\Delta t_i}$$

where V^i_{ep} = volume of the epilimnion in interval i, Δt_i = length of interval i, and q_i = mean rate of inflow water in interval i, we then have

$$\frac{1}{\beta_i} = \frac{1-\varrho_i}{\Delta t_i} = \frac{q_i}{V^i_{ep} + q_i\,\Delta t_i}\ t \tag{3}$$

Substituting (3) into equation (2) gives

$$\Omega_i = \Omega_{oi}\ \exp\left(-\frac{q_i}{V^i_{ep} + q_i\,\Delta t_i}\ t\right) \tag{4}$$

Although V^i_{ep} is constant during interval i, the rate of inflow water usually varies. Therefore the interval i is subdivided into m subintervals, each with a constant rate of inflow water q_{ik} (k=1,.....m) and equation (4) becomes

$$\Omega_i = \Omega_{oi}\ \exp\left(-\sum_{k=1}^{m}\frac{q_{ik}\,\Delta t_k}{V^i_{ep} + q_{ik}\,\Delta t_k}\right)$$

§ 2. The code

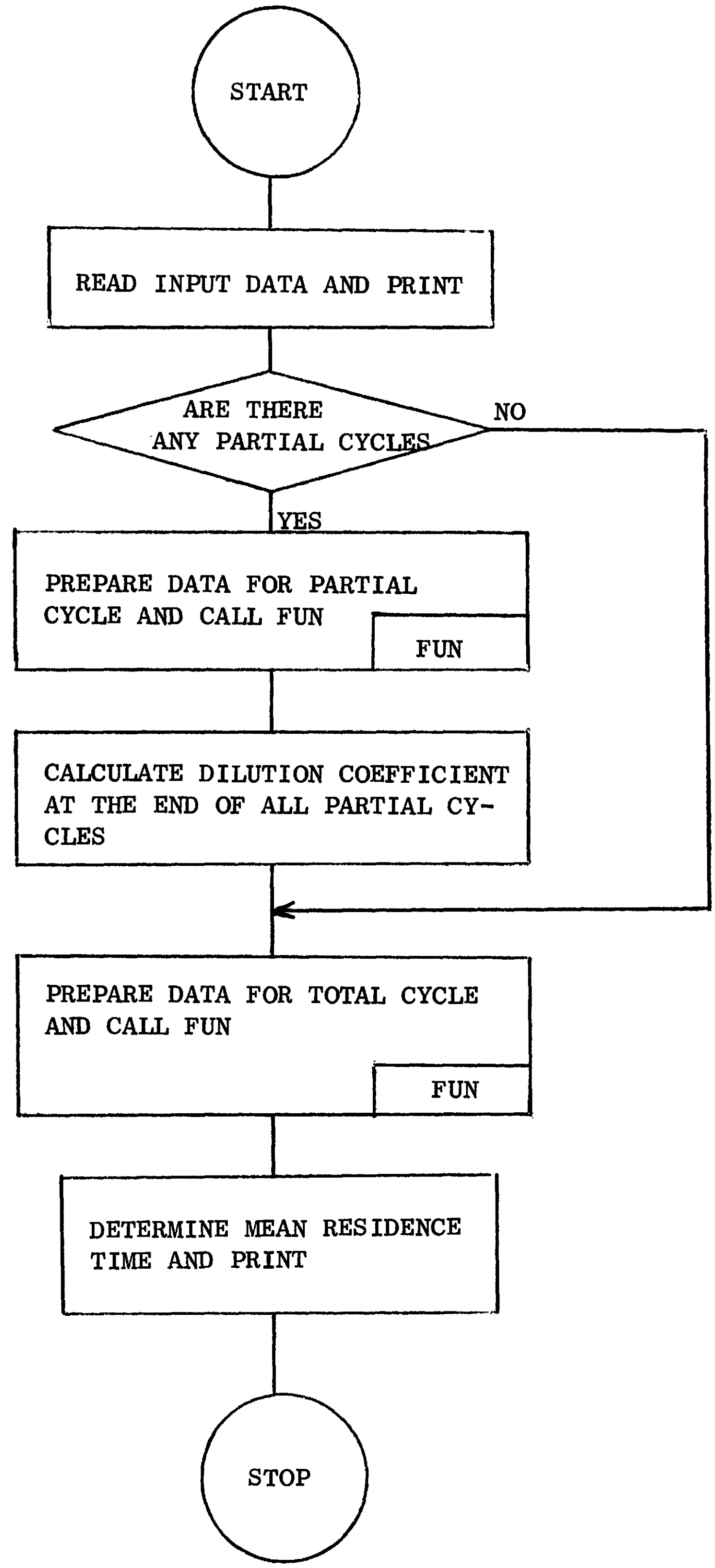
§ 2.1 General Remarks

The program RESIDU is a PL/1 code composed of a main program and one subroutine called FUN. This subroutine calculates α_{ep}, the dilution coefficient for the original water in the epilimnion at the end of an annual cycle.

To facilitate the reading of the code, the following description of the main variables appearing in the program might be useful.

NPAR	number of partial cycles
NTOT	number of total cycles (=1)
NIP	number of intervals in a partial cycle
NIT	number of intervals in the total cycle
V(i)	epilimnion volume (m^3) of interval i in the partial cycle
V1(i)	epilimnion volume (m^3) of interval i in the total cycle
TRANS(j)	average inflow-outflow rate (m^3/day) per month j
DAYS(i)	total number of days in interval i
Q(i)	total volume of transit (inflow-outflow) water (m^3) in interval i
ALFA	α_{ep} = dilution coefficient for the original water at the end of an annual cycle
TAU	τ = mean residence time

§ 2.2 FLOWCHART



§ 2.3 Input description

Card 1 TEXT = title (col. 1-80)

Card 2 NPAR = number of partial cycles.
NIP = number of intervals in the partial cycle.
NIT = number of intervals in the total cycle.

Card 3 TRANS(j) (j=1,12) = average inflow-outflow rate (m^3/day) for each month; 12 values are required.

If NPAR = 0 cards 4, 5 and 6 are omitted.

Card 4 V(i) (i=1,NIP) = epilimnion volume (m^3) of interval i in the partial cycle.

Card 5 N = number of different subintervals of which interval i is composed.

Card 6 NDAYS(k) = number of days of subinterval k.
NMONTH(k) = identification of the month of subinterval k.
Identification code to use:

JAN = january
FEB = february
MAR = march
APR = april
MAY = may
JUN = june
JUL = july
AUG = august
SEP = september
OCT = october
NOV = november
DEC = december

The values NDAYS(k) and NMONTH(k) define the subinterval k (k=1,N).

Cards 5 and 6 are repeated NIP times.

Card 7 V(i) (i=1,NIT) = epilimnion volume (m^3) of interval i in the total cycle.

Card 8 as card 5.

Card 9 as card 6.

Cards 8 and 9 are repeated NIT times.

Further, two general PL/1 rules have to be observed:

1. All input values are separated by blanks and/or commas.
2. All alphanumerical values (as TEXT and NMONTH) are enclosed with quotes.

§ 2.4 Listing of the code

```
--------------------------------------------------------------------------
I                                                                        I
I  RESIDU                                                                I
I    (CALCULATES THE MEAN RESIDENCE TIME OF WATER IN MONOMICTIC LAKES)   I
I                                                                        I
--------------------------------------------------------------------------

NPAR        NUMBER OF PARTIAL CYCLES
NTOT        NUMBER OF TOTAL CYCLES (=1)
NIP         NUMBER OF INTERVALS IN A PARTIAL CYCLE
NIT         NUMBER OF INTERVALS IN THE TOTAL CYCLE
V(I)        EPILIMNION VOLUME (M3) OF INTERVAL I IN THE PARTIAL CYCLE
V1(I)       EPILIMNION VOLUME (M3) OF INTERVAL I IN THE TOTAL CYCLE
TRANS(J)    AVERAGE INFLOW-OUTFLOW RATE (M3/DAY) PER MONTH J
DAYS(I)     TOTAL NUMBER OF DAYS IN INTERVAL I
Q(I)        TOTAL VOLUME OF TRANSIT (INFLOW-OUTFLOW) WATER (M3) IN
                                                             INTERVAL I
ALFA        DILUTION COEFFICIENT FOR THE ORIGINAL WATER AT THE END OF
                                                        AN ANNUAL CYCLE
TAU         MEAN RESIDENCE TIME (YEARS)
--------------------------------------------------------------------------

 AA..PROC OPTIONS (MAIN),.
     DCL  TEXT CHAR(80) VAR,CM(20),.
     DCL  V(20),Q(20),DAYS(20),V1(20),Q1(20),DAYS1(20),.
     DCL  RHO(20),RHO1(20),.
     DCL  NDAYS(*)CTL, NMONTH(*)CHAR(9) CTL,.
     DCL  TRANS(12),.
     DCL  MONS CHAR(48)
               INIT('JAN$FEB$MAR$APR$MAY$JUN$JUL$AUG$SEP$OCT$NOV$DEC$'),.
     ON ERROR SNAP PUT PAGE DATA,.

     PUT PAGE EDIT ('INPUT CARDS',
                    '-----------') (SKIP(4),A,SKIP,A),.  PUT SKIP(5),.
     GET LIST (TEXT,NPAR,NIP,NIT) COPY,.
     GET LIST ((TRANS(I) DO I=1 TO 12)) COPY,.
     NTOT=1,.

     IF NPAR=0 THEN GOTO BB,.
     GET ((V(I) DO I=1 TO NIP)) COPY,.
     DO I=1 TO NIP,.
     GET (N) COPY,.
     ALLOCATE NDAYS(N),NMONTH(N),.
     GET ((NDAYS(M),NMONTH(M) DO M=1 TO N)) COPY,.
```

```
     DAYS(I)=0,.   Q(I)=0,.   SUM=0,.
     DO J=1 TO N,.
     K=(INDEX(MONS,SUBSTR(NMONTH(J),1,3))+3)/4,.
     IF K=0 THEN DO,. PUT EDIT ('MISTAKE IN INPUT DATA',NMONTH(J))
                                    (A,X(3),A),. GOTO EOJ,. END,.
     P=TRANS(K)*NDAYS(J),.
     SUM=SUM+P/(V(I)+P),.
     DAYS(I)=DAYS(I)+NDAYS(J),.
     Q(I)=Q(I)+P,.
     END,.
     RHO(I)=EXP(-SUM),.
     END,.

BB.. GET LIST ((V1(I) DO I=1 TO NIT)) COPY,.
     DO I=1 TO NIT,.
     GET (N) COPY,.
     ALLOCATE NDAYS(N),NMONTH(N),.
     GET ((NDAYS(M),NMONTH(M) DO M=1 TO N)) COPY,.
     DAYS1(I)=0,.   Q1(I)=0,.   SUM=0,.
     DO J=1 TO N,.
     K=(INDEX(MONS,SUBSTR(NMONTH(J),1,3))+3)/4,.
     P=TRANS(K)*NDAYS(J),.
     SUM=SUM+P/(V1(I)+P),.
     DAYS1(I)=DAYS1(I)+NDAYS(J),.
     Q1(I)=Q1(I)+P,.
     END,.
     RHO1(I)=EXP(-SUM),.
     END,.

     PUT PAGE EDIT (TEXT,SUBSTR((80)'=',1,LENGTH(TEXT)))
                         (SKIP(4),A,SKIP,A),.
     PUT SKIP(4) EDIT('AVERAGE INFLOW-OUTFLOW RATE(M3/DAY) PER MONTH',
                      '---------------------------------------------')
                      (A,SKIP),.
     PUT EDIT ((SUBSTR(MONS,1+(I-1)*4,3),TRANS(I) DO I=1 TO 12))
                 (SKIP,A,X(3),F(15,5,7)),.
     PUT SKIP(3) EDIT
     ('INTERVAL','DAYS','VOL. EPILIMNION(M3)','VOL. TRANSIT WATER(M3)',
     '--------','----','-------------------','----------------------')
                          (COL(28),A,COL(40),A,COL(52),A,COL(75),A),.

     IF NPAR=0 THEN GOTO CC,.
     PUT EDIT ('PARTIAL CYCLE') (SKIP(2),COL(11),A),.
F1.. FORMAT (COL(28),F(5),COL(40),F(4),COL(52),E(13,3,5),COL(75),
               E(14,3,5)),.
     DO I=1 TO NIP,.
     PUT EDIT(I,DAYS(I),V(I),Q(I)) (R(F1)),.END,.
CC.. PUT EDIT ('TOTAL CYCLE') (SKIP(2),COL(11),A),.
     DO I=1 TO NIT,.
```

```
      PUT EDIT (I,DAYS1(I),V1(I),Q1(I))(R(F1)),. END,.

      PUT EDIT ('NUMBER OF PARTIAL CYCLES =',NPAR,
                'NUMBER OF TOTAL CYCLES =',NTOT)
                (SKIP(4),COL(15),A,F(3),SKIP,COL(17),A,F(3)),.
      IF NPAR=0 THEN GOTO FF,.
      PUT EDIT ('NUMBER OF INTERVALS IN PARTIAL CYCLE =',NIP)
                (COL(3),A,F(3)),.
 FF.. PUT EDIT ('NUMBER OF INTERVALS IN TOTAL CYCLE =',NIT)
                (COL(5),A,F(3)),. PUT SKIP(3),.

      T=NPAR+NTOT,.
      WEP=1,.
      IF NPAR=0 THEN DO,. ALFA=1,. NTOT=0,. GOTO DD,. END,.
      WEP=FUN(NIP,V,RHO,WEP,OM,0),.
      PUT EDIT('ALFA AFTER   1 YEAR   =',WEP,'  PERCENT')
              (X(1),A,F(9,3,2),A),.
      ALFA=WEP**NPAR,.

 DD.. ALFA=FUN(NIT,V1,RHO1,ALFA,OM,NTOT),.
      PUT EDIT('ALFA AFTER',T,'YEAR','S',' ',' =',ALFA,'  PERCENT')
           (SKIP,X(1),A,F(4),X(1),A,A(T GT 1),A(T LE 1),A,F(9,3,2),A),.
      TAU=T/2*(1+ALFA)/(1-ALFA),.

      PUT EDIT('MEAN RESIDENCE TIME =',TAU,'  YEARS')
              (SKIP(3),X(2),A,F(9,3),A),.
EOJ.. END AA,.


FUN.. PROC(N,V,RHO,WEP,OM,NTOT),.

      DCL  V(*),RHO(*),OM(*),.

      DO I=1 TO N,.
      IF I=1 THEN GO TO BB,.
      IF I NE 2 THEN GO TO CC,.
      WN=WEP,.
      WEP=OM(1)/V(1),.

 BB.. OMO=V(I)*WEP,. GO TO EE,.

 CC.. IF V(I) LE V(1) THEN GO TO DD,.
      WEP=1,.
      IF NTOT=1 AND I NE N THEN WEP=WN,.

 DD.. OMO=OM(I-1)+(V(I)-V(I-1))*WEP,.

 EE.. OM(I)=RHO(I)*OMO,.
      END,.
      RETURN(OM(N)/V(N)),.
      END FUN,.
```

§ 2.5 Some examples

The code has been applied to the Lake Maggiore (Italy), to the Lake Lugano and the Bay of Agno (Switzerland).

Lake Maggiore has a pluriannual cycle composed of 5 equal years with a partial turnover, followed by 1 year with a total turnover, while Lake Lugano has a pluriannual cycle of 9 equal years with a partial turnover and then 1 year with a total turnover.

The Bay of Agno is characterized by an annual cycle with a total turnover.

Table I presents some significant data concerning the different examples, together with the values for the mean residence time.

Table I

	number of partial cycles	number of intervals in partial cycle	number of intervals in total cycle	α_{ep} at the end of the 1^{st} partial cycle	α at the end of the total cycle	mean residence time (years)
Lake Maggiore	5	7	8	81,582 %	67,245 %	15,318
Lake Lugano	9	7	8	85,438 %	51,273 %	15,523
Bay of Agno	0	-	7	-	64.248 %	2.297

INPUT CARDS

```
'LAKE  MAGGIORE'
  5  7  8
  12.5E+6   12.3E+6   13.0E+6   22.3E+6   33.9E+6   43.2E+6
  35.0E+6   27.4E+6   28.9E+6   23.1E+6   23.9E+6   17.9E+6
  95.0E+8   20.8E+8   40.7E+3   55.8E+3   77.9E+8   95.0E+3   174.E+3
  1
  15 'MAR'
  8
  30 'APR'  31 'MAY'  30 'JUN'  31 'JUL'  31 'AUG'  30 'SEP'  31 'UCT'  15 'NOV'
2
  15 'NOV'  16 'DEC'
  1
  15 'DEC'
  1
  16 'JAN'
  2
  15 'JAN'  15 'FEB'
  2
  13 'FEB'  16 'MAR'
  55.0E+8   20.8E+8   40.7E+3   55.8E+3   77.9E+8   95.0E+3   174.E+3   377.E+8
  1
  15 'MAR'
  8
  30 'APR'  31 'MAY'  30 'JUN'  31 'JUL'  31 'AUG'  30 'SEP'  31 'UCT'  15 'NOV'
2
  15 'NOV'  16 'DEC'
  1
  15 'DEC'
  1
  16 'JAN'
  2
  15 'JAN'  15 'FEB'
  1
  13 'FEB'
  1
  16 'MAR'
```

LAKE MAGGIORE

AVERAGE INFLOW-OUTFLOW RATE(M3/DAY) PER MONTH

JAN	12.50000E+06
FEB	12.30000E+06
MAR	13.00000E+06
APR	22.50000E+06
MAY	38.90000E+06
JUN	45.20000E+06
JUL	35.00000E+06
AUG	27.40000E+06
SEP	26.90000E+06
OCT	28.10000E+06
NOV	28.90000E+06
DEC	17.90000E+06

	INTERVAL	DAYS	VOL. EPILIMNION(M3)	VOL. TRANSIT WATER(M3)
PARTIAL CYCLE	1	15	95.000E+08	19.500E+07
	2	229	20.800E+08	72.829E+08
	3	31	40.700E+08	71.990E+07
	4	15	59.800E+08	26.850E+07
	5	16	77.900E+08	20.000E+07
	6	30	95.000E+08	37.200E+07
	7	29	17.400E+09	36.790E+07
TOTAL CYCLE	1	15	95.000E+08	19.500E+07
	2	229	20.800E+08	72.829E+08
	3	31	40.700E+08	71.990E+07
	4	15	59.800E+08	26.850E+07
	5	16	77.900E+08	20.000E+07
	6	30	95.000E+08	37.200E+07
	7	13	17.400E+09	15.990E+07
	8	16	37.700E+09	20.800E+07

NUMBER OF PARTIAL CYCLES = 5
NUMBER OF TOTAL CYCLES = 1
NUMBER OF INTERVALS IN PARTIAL CYCLE = 7
NUMBER OF INTERVALS IN TOTAL CYCLE = 8

ALFA AFTER 1 YEAR = 81.582 PERCENT
ALFA AFTER 6 YEARS = 67.245 PERCENT

MEAN RESIDENCE TIME = 15.318 YEARS

INPUT CARDS

```
'LAKE OF LUGANO'
  9  7  8
  1599580.  1228880.  1833330.  2410530.  3196800.  2389440.
  2211840.  1702080.  1797120.  2160000.  3067200.  2082240.
  2195.8E+6 522.6E+6 573.2E+6 1405.2E+6 1314.E+6 2195.8E+6 3552.9E+6
  1
  16 'MAR'
  7
  30 'APR'   31 'MAY'   30 'JUN'   31 'JUL'   31 'AUG'   30 'SEP'   15 'OCT'
  2
  16 'OCT'   15 'NOV'
  2
  15 'NOV'   15 'DEC'
  2
  16 'DEC'   15 'JAN'
  2
  16 'JAN'   15 'FEB'
  2
  13 'FEB'   15 'MAR'
  2195.8E+6 522.6E+6 573.2E+6 1405.2E+6 1314.E+6 2195.8E+6 3552.9E+6 5794.2E+6
  1
  16 'MAR'
  7
  30 'APR'   31 'MAY'   30 'JUN'   31 'JUL'   31 'AUG'   30 'SEP'   15 'OCT'
  2
  16 'OCT'   15 'NOV'
  2
  15 'NOV'   15 'DEC'
  2
  16 'DEC'   15 'JAN'
  2
  16 'JAN'   15 'FEB'
  1
  13 'FEB'
  1
  15 'MAR'
```

LAKE OF LUGANO

AVERAGE INFLOW-OUTFLOW RATE(M3/DAY) PER MONTH

JAN	13.99680E+05
FEB	12.26880E+05
MAR	14.86080E+05
APR	24.10560E+05
MAY	31.96800E+05
JUN	29.89440E+05
JUL	22.11840E+05
AUG	17.02080E+05
SEP	17.97120E+05
OCT	21.60000E+05
NOV	30.67200E+05
DEC	20.82240E+05

	INTERVAL	DAYS	VOL. EPILIMNION(M3)	VOL. TRANSIT WATER(M3)
PARTIAL CYCLE	1	16	21.958E+08	23.777E+06
	2	198	52.260E+07	46.875E+07
	3	31	97.320E+07	80.568E+06
	4	30	14.052E+08	77.242E+06
	5	31	18.140E+08	54.311E+06
	6	31	21.958E+08	40.798E+06
	7	28	35.529E+08	38.241E+06
TOTAL CYCLE	1	16	21.958E+08	23.777E+06
	2	198	52.260E+07	46.875E+07
	3	31	97.320E+07	80.568E+06
	4	30	14.052E+08	77.242E+06
	5	31	18.140E+08	54.311E+06
	6	31	21.958E+08	40.798E+06
	7	13	35.529E+08	15.949E+06
	8	15	57.942E+08	22.291E+06

NUMBER OF PARTIAL CYCLES = 9
NUMBER OF TOTAL CYCLES = 1
NUMBER OF INTERVALS IN PARTIAL CYCLE = 7
NUMBER OF INTERVALS IN TOTAL CYCLE = 8

ALFA AFTER 1 YEAR = 85.438 PERCENT
ALFA AFTER 10 YEARS = 51.273 PERCENT

MEAN RESIDENCE TIME = 15.523 YEARS

INPUT CARDS

```
'BAY OF AGNO'
 0  0  7
 131328.  177120.  252233.  500246.  533324.  531792.
 259200.  215136.  433728.  310176.  447552.  257904.
 86.77E+6  21.67E+6  39.77E+6  56.67E+6  72.37E+6  86.77E+6  116.07E+6
 1
 16 'MAR'
 7
 30 'APR'  31 'MAY'  30 'JUN'  31 'JUL'  31 'AUG'  30 'SEP'  15 'OCT'
 2
 16 'OCT'  15 'NOV'
 2
 15 'NOV'  15 'DEC'
 2
 16 'DEC'  15 'JAN'
 2
 16 'JAN'  15 'FEB'
 2
 13 'FEB'  15 'MAR'
```

BAY OF AGNO
===========

AVERAGE INFLOW-OUTFLOW RATE(M3/DAY) PER MONTH

JAN	13.13280E+04
FEB	17.71200E+04
MAR	25.22880E+04
APR	50.02460E+04
MAY	55.38240E+04
JUN	53.17920E+04
JUL	25.92000E+04
AUG	21.51360E+04
SEP	43.37280E+04
OCT	31.01760E+04
NOV	44.75520E+04
DEC	25.79040E+04

	INTERVAL	DAYS	VOL. EPILIMNION(M3)	VOL. TRANSIT WATER(M3)
TOTAL CYCLE	1	16	86.770E+06	40.366E+05
	2	198	21.670E+06	80.499E+06
	3	31	39.770E+06	11.676E+06
	4	30	56.670E+06	10.582E+06
	5	31	72.370E+06	60.964E+05
	6	31	86.770E+06	47.580E+05
	7	28	11.607E+07	60.869E+05

NUMBER OF PARTIAL CYCLES = 0
NUMBER OF TOTAL CYCLES = 1
NUMBER OF INTERVALS IN TOTAL CYCLE = 7

ALFA AFTER 1 YEAR = 64.248 PERCENT

MEAN RESIDENCE TIME = 2.297 YEARS

References

1) R. Piontelli e V. Tonolli - Il tempo di residenza delle acque lacustri in relazione ai fenomeni di arricchimento in sostanze immesse, con particolare riguardo al Lago Maggiore. Mem. Ist. Ital. Idrobiol., 17, 247-266 (1964).

2) G. Rossi, V. Ardente, F. Beonio -Brocchieri, E. Diana - Il tempo medio di residenza delle acque nel Lago di Lugano, da pubblicare (1974).