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Software for Design of Water Harvesting Ponds and Associated Structures

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SUMMARY

Hydrologic design parameters (i.e. design rainfall, runoff and peak flow rate) database need to be developed on region basis for proper design of water harvesting structures in country's on-going watershed development programmes at large scale. Software for the design of water harvesting pond and associated structures has been developed to make the designing task easy and simple. The software is developed using Visual Basic as front end and Microsoft Access as back end. The software has four basic modules – hydrologic design, hydraulic design, structural design and estimation of materials and costs of water harvesting structures. Hydrologic design module consists of three sub-modules of rainfall frequency analysis for design rainfall, design runoff volume and design peak flow estimation. Hydraulic design module consists of five sub-modules for determination of storage capacity of pond based on Krimgold and Harold (1944) equation and crop water requirement, storage structure dimensions, spillway dimensions, and design of earthen embankment including seepage analysis. The structural design module includes two sub-modules of structures subjected to water pressure and earth pressures for checking the stability of water harvesting structures. The materials and costs estimation module consists of four sub modules related to different components. The software uses inbuilt database for different variables of formulae/equations used in runoff and peak flow estimation for ten identified districts of Madhya Pradesh (MP**)**, India. The developed software was used to create database of design rainfall, runoff volume and peak flow and design of water harvesting structures in Vertisols.

Keywords: Hydrologic design parameters, Frequency analysis, Database, Rainfall, Runoff .

1. INTRODUCTION

The increasing worldwide shortages of water and costs of irrigation are leading to an emphasis on creation of additional water storage through rain water harvesting and its recycling for enhancing crop production. Hydrologic variables (rainfall, runoff and peak flow) are key parameters in design of water harvesting structures. Rainfall generated runoff is very important in various activities of water resources development and watershed management (Mishra *et al*. 2013). Rainfall Intensity-Duration-Frequency (IDF) relationship is most important parameter for design of various hydrologic and water harvesting structures. Many researchers have developed various formulae for design rainfall/storm estimation based on the construction of IDF curves using (Rakhecha and Clark 1999, Durbude 2008,). Standard probability distributions commonly used for design rainfall/flood estimation are Normal, log Normal (LN), Pearson, log Pearson type-III (LP-III), and Extreme value type-1 (Wilson 1990, Haktan 1992, Al-Hassoun 2011). The soil conservation service curve number (SCS-CN) method (SCS 1956) converts rainfall to surface runoff (or rainfall-excess) using a CN derived from watershed characteristics and 5-days antecedent rainfall. This method is based on recharge capacity of a watershed. Rational method is used world wide for estimation of peak flow rate with reasonable accuracy for the watersheds having drainage area less than 1000 ha.

Rainwater harvesting technology is highly location-specific and practices evolved in a given region have a limited applicability in other regions. General guidelines are inadequate for the design and adoption of water harvesting structures in different regions of the country (Sharma *et al*. 2002). Water harvesting and recycling studies carried out at CIAE,

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Bhopal revealed that water harvesting pond of 3 m minimum depth can be constructed in 10-12 per cent of watershed area (Bhandarkar *et al*. 2005). The proper planning, design and execution of site- specific rainwater harvesting structures in country's on-going watershed development and management programmes at large scale got utmost importance. Therefore, there is a need to develop software and databases of design parameters considering local conditions, which will arrive at proper design of water harvesting pond. The development of software will simplify the design of water harvesting ponds and associated inlet-outlet structures so that field engineers including farmers can design these structures in his own style.

2. MATERIALS AND METHODS

This section includes development platform, minimum system requirement and description of design software modules supported with theoretical background.

2.1 Development Platform and Minimum System Requirements

The software for design of harvesting pond and associated structures soil and water conservation structures was developed using Microsoft Visual Basic 6.0 Enterprise Edition with Service Pack 6, for 32-bit Windows Development and Microsoft Access 2000 as backend.

Intel® Pentium™ IV 700MHz or equivalent processor

128 MB RAM.

60 MB Hard disk space.

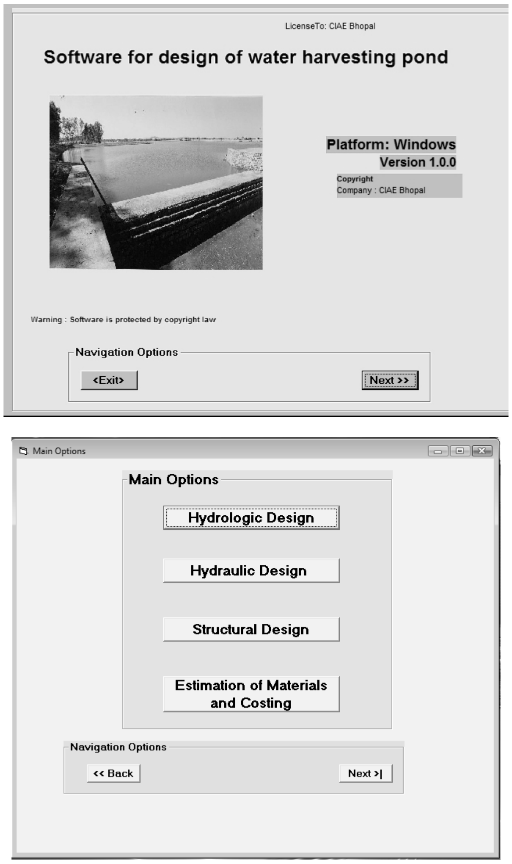
VGA display with 1024 × 768 Pixels resolution.

Microsoft® Windows™ 98 or above.

Microsoft® Visual Basic Runtime Installed

2.2 Description of Software for Design of Water Harvesting Structures

The software has four basic modules – hydrologic design, hydraulic design, structural design of water harvesting structures (ponds and associated structures) and estimation of materials and costs of water harvesting structures. Splash and main screens of the developed software are shown in Fig. 1**.** Procedural steps block diagramme for development of database of design parameters of water harvesting pond is given in Fig. 2(a).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Software for design of water harvesting pond

Platform: Windows

Version 1.0.0

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Fig. 1. Splash and main screens of the developed software

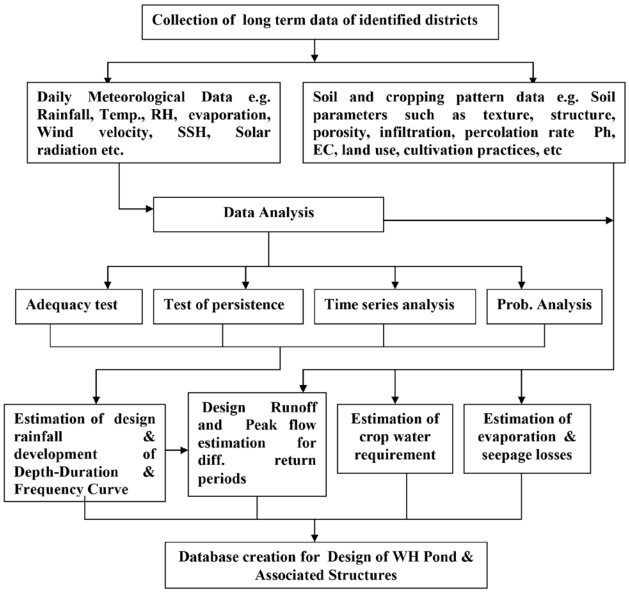


Fig. 2(a). Software block diagramme showing procedural steps followed for database creation

2.2.1 Software architecture

The software architecture consisting of data flow diagramme and decision rules for design and const estimation of water harvesting pond and associated structures is shown in Fig. 2(b). This software has been supported with database that contains data of 10 locations spread all over Madhya Pradesh State in India to make the design location specific. The software is armed with database addition and editing facility for designing of water harvesting ponds at desired locations.

2.2.2 Hydrologic design module

Hydrologic design module consists of three sub-modules of rainfall frequency analysis, design runoff volume estimation and design peak flow estimation using Rational method.

2.2.2.1 *Rainfall frequency analysis sub module*

The rainfall frequency analysis module consists of data adequacy test, persistence/randomness test, identification of best probability density function from nine pdfs based on minimum value of Chi Square parameter values. The software uses following nine probability density functions (pdfs) for rainfall frequency analysis.

- Normal Distribution (N) and Log Normal Distribution (LN)
- Extreme Values Type Distribution (EVT)-I
- Log-Extreme Values Type Distribution (LEVT-I)
- Exponential (EXP) Distribution and Log Exponential (LEXP) Distribution
- Pearson Type-III (PT-III) Distribution and Log-Pearson Type-III (LPT-III) Distribution
- Weibull Distribution

The pdfs and parameters of distributions are given in Table 1.

Table 1. The probability functions selected for rainfall frequency analysis

Distribution Function	Probability Density Function (Pdf)	Parameters	Mean	Variance
Two Parameter Normal (N_2)	$f(x)=\frac{1}{\sigma\sqrt{2\pi}}\exp[\frac{1}{2}(x-\mu)^2/\sigma^2]$	m , σ	m	σ^2
Two Parameter Log-Normal (LN_2)	$f(x)=\frac{\exp[-\frac{1}{2}(nx-\sigma_y)^2/\sigma_y^2]}{\sqrt{2\pi\sim x^2\sigma_y^2}}$ where y = ln x	m_y , σ_y	$e^{\mu_y+\sigma_y^2/2}$	$\mu_y^2(e^{\sigma_y^2+1})$
Extreme value Type-I (EVT-I)	$f\left(x\right)=\exp((-y-e^{-y})$ where y = (x–β)/α	α, β	$\beta + 0.577\ \alpha$	$1.645\ \alpha^2$
Log Extreme value Type-I (LEVT-I)	$f\left(x\right)=\exp((-y-e^{-x})$ where y = (ln x–β)/α	α, β	$\beta + 0.577\ \alpha$	$1.645\ \alpha^2$
Exponential (EXP)	$p_x(x)=\lambda e^{-\lambda x}$ where x>0, λ>0	λ	$1/\lambda$	$1/\lambda^2$
Log-Exponential (LEXP)	$p_x(x)=\lambda e^{-\lambda y}$ where y= ln x , x >0, λ >0	λ	$1/\lambda$	$1/\lambda^2$
Pearson Type III (Gamma) (PT_3)	$f(x)=\frac{\lambda^n y^{n-1}e^{-\lambda x}}{\Gamma(n)}$	n, λ	n/λ	n/λ^2
Log-Pearson Type III (LPT_3)	$f(x)=\frac{\lambda^n y^{n-1}e^{-\lambda y}}{\Gamma(n)}$ where y = ln x	n, λ	n/λ	n/λ^2
Weibull	$p_x(x)=\alpha x^{\alpha-1}\beta^{-\alpha}\exp[-(x/\beta)^{\alpha}$	$\alpha, \beta > 0$	$\beta\Gamma(1+1/\alpha)$	$\beta^2[\Gamma(1+2/\alpha)$ $-\Gamma^2(1+1/\alpha)]$

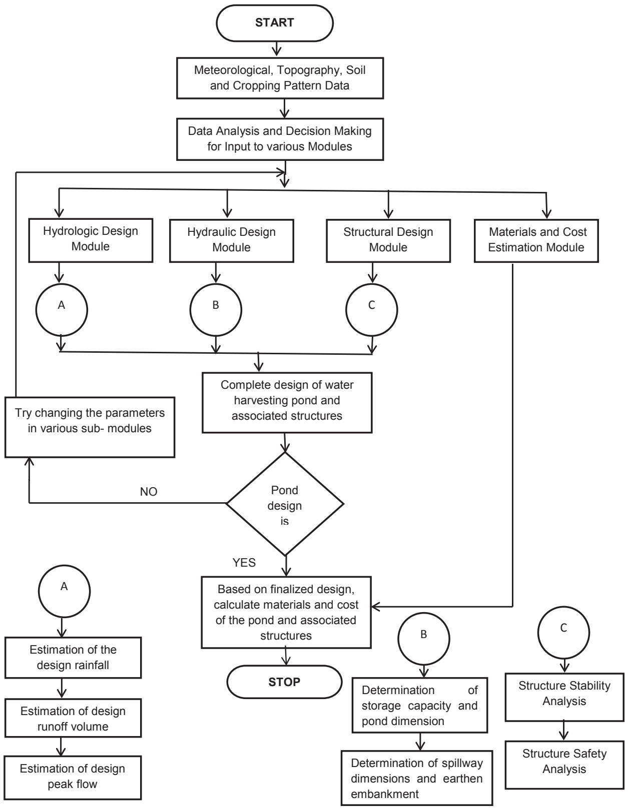


Fig. 2(b). Complete software architecture including decision rules

Chi square goodness-of-fit test is applied to judge the fitting of a particular probability distribution.

$$\chi^2 = \sum_{i=1}^{k} (O_i - E_i)^2 / E_i \qquad (1)$$

where, k = number of class intervals,

O_i = observed values and

E_i = expected number of observations in the i^{th} class.

Degree of freedom (DF) = $k - p - 1$, where, p = No. of parameters of distribution.

The hypothesis that the data from the expected distribution is rejected if $\chi_c^2 > \chi^2_{1-\alpha,\ k-p-1}$ for α level of significance.

pdf is considered to be fitted well (accepted) if the calculated Chi square value is less than the table value of Chi square for DF =2 at 95% confidence level (=5.99).

The best fitted pdf describing data set and giving minimum value Chi-Square test parameter can be identified for estimating the design values of the variable with different probability levels (Return periods). Design rainfall values were estimated using following relationship

$$X_T = X_{mean}(1 + C_v K_T) \qquad (2)$$

where, X_T = magnitude of the variable (rainfall) having a return period T,

C_v = coefficient of variation and

K_T = frequency factor for the distribution function. (Haan *et al*. 1994).

The magnitudes of 1-day-max, 2-day-max, monthly and annual rainfall at various return periods can be estimated using best fitted pdf.

The screen for rainfall frequency analysis is shown in Fig. 3.

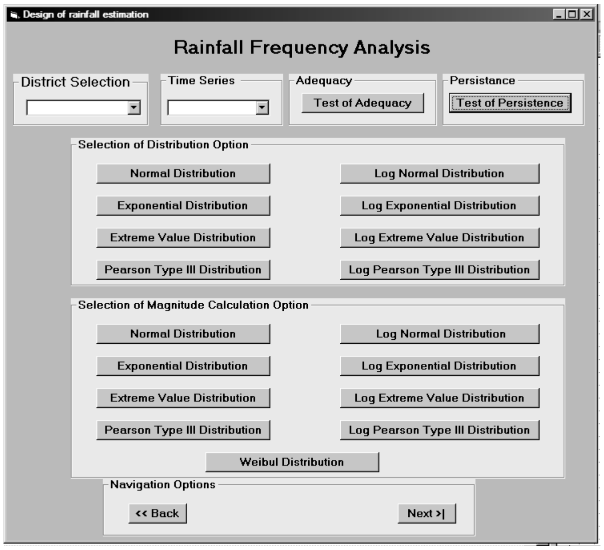


Fig. 3. Screen for rainfall frequency analysis

2.2.2.2 *Design runoff volume estimation module*

Natural Resource Conservation Service (NRCS) – Curve Number (CN) method was used for estimation of design runoff values for black soil region.

$$Q = \frac{(P - I_a)^2}{(P + I_a) + S} \qquad (3)$$

Considering I_a = 0.1S for Vertisols region, the above equation becomes

$$Q = \frac{(P - 0.1S)^2}{(P + 0.9S)} \text{ and } CN = \frac{25400}{(S + 254)}$$

where,

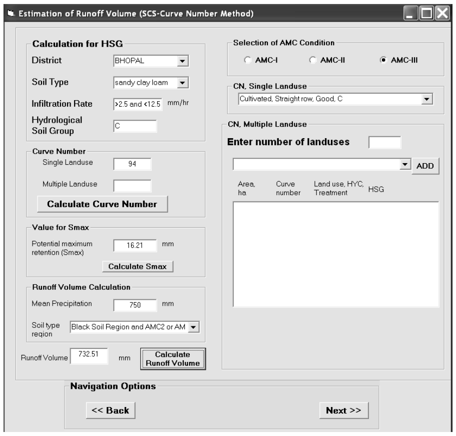
Q = runoff depth in mm

I_a = initial abstraction during the period between the beginning of rainfall and runoff in equivalent depth over the watershed

S = potential retention in mm and

P = rainfall in mm

For estimation of design runoff, curve numbers from curve number table suggested by Ministry of Agriculture, Hydrology Division, Govt. of India (1972) were obtained for the wet soil condition i.e. antecedent soil moisture condition (AMC-III) and good hydrologic condition and straight row crop cultivation practice (Table 2). For Black soils region AMC-II and III, for estimation of design average annual runoff $I_a = 0.1S$ and for all other regions Ia = 0.3S was considered. The software screen for estimation of design runoff volumes is shown in Fig. 4.


Estimation of Runoff Volume (SCS-Curve Number Method)

Calculation for HSG

District: BHOPAL

Soil Type: sandy clay loam

Infiltration Rate: >2.5 and <12.5 mm/hr

Hydrological Soil Group: C

Curve Number

Single Landuse: 94

Multiple Landuse:

Value for Smax

Potential maximum retention (Smax): 16.21 mm

Runoff Volume Calculation

Mean Precipitation: 750 mm

Soil type region: Black Soil Region and AMC2 or AM

Runoff Volume: 732.51 mm

Selection of AMC Condition

○ AMC-I ○ AMC-II ● AMC-III

CN, Single Landuse

Cultivated, Straight row, Good, C

CN, Multiple Landuse

Enter number of landuses:

Fig. 4. Screen for estimation of runoff volume

2.2.2.3 *Design peak flow estimation module*

This module uses two methods for estimation of designed peak flow. For watersheds upto 1000 ha area, the most commonly used relation is *Rational Formula* to estimate the peak flow rate and is given as

$$Q_p = \frac{CIA}{360} \tag{4}$$

where

Q_p = the peak discharge in m^3/s,

I = rainfall intensity of a desired recurrence interval and for the duration of time of concentration (Tc) of the watershed in mm/h.

A = watershed area in ha,

C = coefficient varying between 0 and 1 (for agricultural cultivated land

Having land slope 0 - 5%, the C varies from 0.5 to 0.6)

The time of concentration, which is needed for selecting an appropriate value of I in the Rational formula, can be calculated by either of the following:

$$T_c = 0.0195 L^{0.779} S^{-0.385} \tag{5}$$

where,

T_c = time of concentration in hours,

L = maximum length of flow in m, and

S = the average slope of the watershed in fraction.

Table 2. Soil and land use conditions considered in design runoff estimation

District	Soil type	Hydrologic Condition	HSG	CN		LULC
				AMC-II	AMC-III	
Bhopal	Sandy clay loam	Good	C	85	94	Cultivated straight row
Indore	Clay	Good	D	89	96	Cultivated straight row
Raisen	Sand clay loam	Good	C	85	94	Cultivated straight row
Hoshangabad	Sand clay loam	Good	C	85	94	Cultivated straight row
Khandawa	Clay	Good	D	89	96	Cultivated straight row
Jabalpur	Clay	Good	D	89	96	Cultivated straight row
Datia	Sandy clay loam	Good	C	85	94	Cultivated straight row
Dhar	Sand clay loam	Good	C	85	94	Cultivated straight row
Guna	Sand clay loam	Good	C	85	94	Cultivated straight row
Chhindwara	Clay	Good	D	89	96	Cultivated straight row

The rainfall intensity value as input to rational method for a given storm duration equal to time of concentration (t_c) and return period (T-years) were estimated using following relationship :

$$I = \frac{KT^a}{(t_c + b)^n} \qquad (6)$$

where,

I = rainfall Intensity (cm/h),

T = return period (years)

t_C = storm duration equal to time of concentration (hours)

The values for K, a, b, and n for particular places in Central Zone were taken from Table 3.

Table 3. Intensity –duration-return period relationships, India

Zone	Station	K	a	b	N
Central Zone	Bagra-Tawa	8.5704	0.2214	1.25	0.9931
	Bhopal	6.9296	0.1892	0.50	0,8767
	Indore	6.9280	0.1394	0.50	1.0651
	Jabalpur	11.379	0.1746	1.25	1.1206
	Jagdalpur	4.7065	0.1084	0.25	0.9902
	Nagpur	11.45	0.1560	1,25	1.0324
	Punasa	4.7011	0.2608	0.50	0.8653
	Raipur	4.683	0.1389	0.15	0.9284
	Thikri	6.088	0.1747	1.00	0.8587
	Central zone	*7.4645*	*0.1712*	*0.75*	*0.9599*

Source: Singh Gurmel *et.al.* (1994).

Ogrosky and Mockus (1957) developed the method to determine the peak runoff rate by using the curve number method. They suggested employing the following formula to determine the peak rate of runoff by using the 6-hour rainfall as the design frequency of small watersheds.

$$q_{peak} = \frac{0.0208 * A * Q_d}{T_p}$$

where

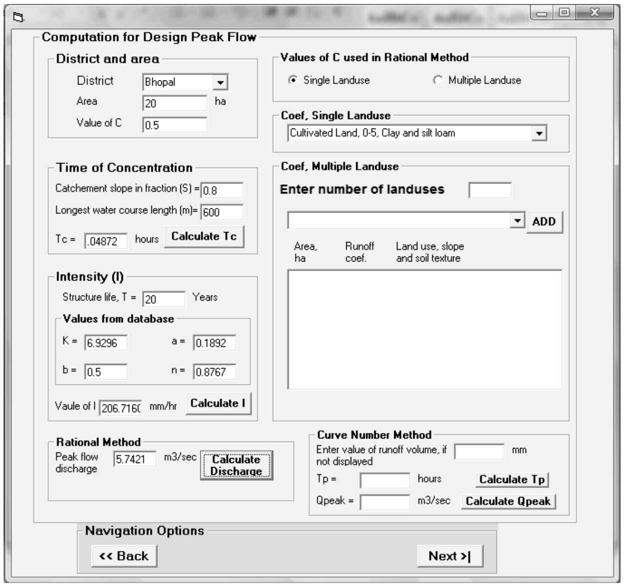
q_{peak} = peak rate of runoff,m^3/s and

A = area, ha

Q_d = Runoff depth, cm, Computed using CN method

T_p = Time to peak, hour = 0.6 $T_c + \sqrt{T_c}$

T_c = Time of concentration in hour



District: Bhopal

Area: 20 ha

Value of C: 0.5

Coef, Single Landuse: Cultivated Land, 0-5, Clay and silt loam

Catchement slope in fraction (S) = 0.8

Longest water course length (m)= 600

Tc = .04872 hours

Structure life, T = 20 Years

K = 6.9296

a = 0.1892

b = 0.5

n = 0.8767

Vaule of I 206.716(mm/hr

Peak flow discharge 5.7421 m3/sec

Enter value of runoff volume, if not displayed mm

Tp = hours

Qpeak = m3/sec

Fig. 5. Screen for estimation of peak flow rate

2.2.3 Hydraulic design module

Hydraulic design module consists of five sub-modules for determination of storage capacity of pond based on Krimgold and Harold (1944) equation and crop water requirement, storage dimensions of the water harvesting structure e.g. height of dam and depth of pond, fixing of spillway dimensions for safe disposal of design peak flow, and design of earthen embankment including seepage analysis. Main screen for hydraulic design of structure is shown in Fig. 6.

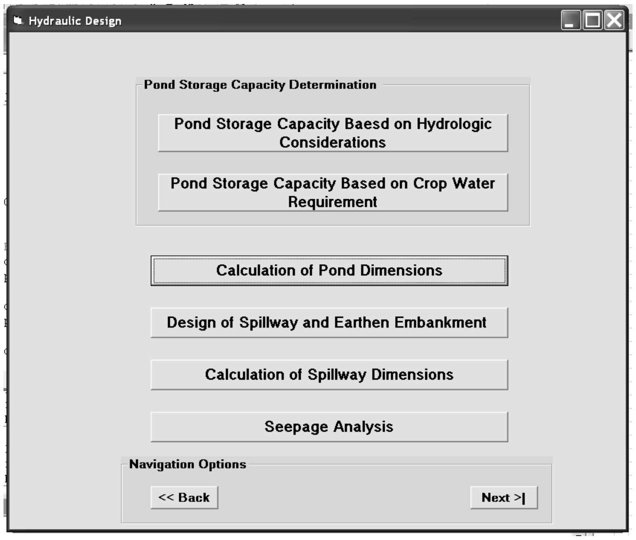


Fig. 6. Screen for hydraulic design of structures

For period (Kharif) under consideration the month taken to be July to September for design of surface fed ponds. For design of this type of pond following *Krimgold Equation* can be used.

$$\frac{RA}{a}+P-\left(E+\frac{U}{a}+S\right)=d+\frac{W}{a} \qquad (8)$$

where

A = Area of watershed, ha

R = Runoff, from the rainfall, *m*

P = Precipitation, (rainfall), *m*

U = Irrigation (kharif) volume, ha-*m*

S = Loss of water due to seepage, *m*

E = Loss of water due to evaporation, *m*

d = Depth of pond, *m*

W = Waste weir flow ha-*m* (nil)

a = Mean surface area of pond, ha

$a = Lb + (bz + Lz)\, d + (2z^2)\, d^2 \times 10^{-4}$

where ,

L = Length at the bottom of pond, *m*

d = Depth of pond, *m*

b = Breadth at the bottom of pond, *m*

z = Side slope, 2 : 1 (H : V)

2.2.4 Structural design module

The structural design of water harvesting structure includes the determination of size of bund/embankment based on stability criteria. This aims at fixing the dimensions of the structural body components and their material of construction to withstand static and dynamic forces acting on the structure. The forces include i) hydrostatic water pressure, ii) weight of the dam, and iii) uplift pressure. The structural design module includes two sub-modules of structures subjected to water pressure and structures subjected to earth pressures. The structural design checks the stability of water harvesting structures for safety against overturning, sliding, tension and compression stresses. (Fig. 7)

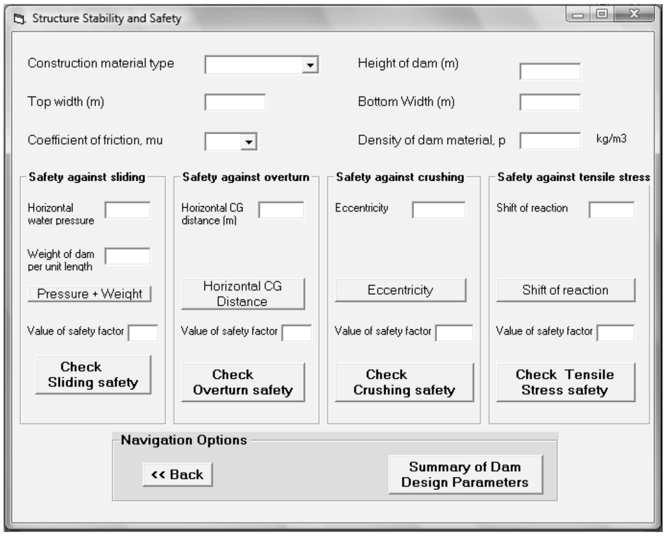


Fig. 7. Screen for structural (stability & safety) analysis

2.2.4.1 *Structures subjected to water pressure*

Structural design considerations for structures subjected to water pressure are given below:

(i) *Equilibrium conditions:* For the structure to be in equilibrium, the following conditions must be satisfied:

- The algebraic sum of all the vertical forces must be zero, i.e. $\sum V=0$
- The algebraic sum of all the horizontal forces must be zero, i.e. $\sum H=0$
- The moment of all forces acting on the wall about point B must be zero to check its overturning, i.e. $\sum M = 0$

(ii) *Condition of stability* : A structure can fail in following ways:

- it may slide forward
- it may overturn
- the material may get crushed due to the maximum compressive stress acting normal to the section, and
- the tensile stress set up in the section and cause its failure. Therefore, the tension should be avoided and for *that the resultant must be within the middle third of the base.*

2.2.4.2 *Structures subjected to earth pressure*

When structure is subjected to earthfill behind the wall, the pressure (Ps) is given as:

$$P_s(kg/m) = \frac{W_s H^2}{2}\left[\frac{1-\sin\theta}{1+\sin\theta}\right] \qquad (8)$$

where, W_s is density of soil or fill material or unit saturated weight of the soil (kgm^{-3}). The term (1-sinq)/(1+sinq) where q is the angle of repose or the angle of internal friction of the soil, represents the ratio of lateral to vertical pressure. The value of q depends on the nature of earth and its wetness shown in Table 4.

Table 4. Angle of repose and unit weights

Substance	Angle of repose	Unit weight
Sand, dry	30^0 - 37^0	1.45 – 1.90
Sand, wet	26^0	1.45 – 1.90
Earth, dry	29^0	1.60 – 1.92
Earth, moist	45^0 - 49^0	1.60 – 1.92
Clay, dry	29^0	1.92 – 2.20
Clay, damp	45^0	1.92 – 2.20
Gravel, clean	48^0	1.45 – 1.75
Gravel with sand	26^0	1.45 – 1.75

2.2.5 Materials and cost estimation module

The materials and costs estimation module consists of four sub modules related to different components. To estimate the quantity of earth work (EW) and materials used in the construction of water harvesting pond and inlet and outlet (waste weir) structures, the developed sub-main screen of software is shown in Fig. 8. The sub main screen consists of four sub modules screen related to different components as given below :

- Screen for estimates of excavation/ earthwork volume and cost for WH pond.
- Screen for Estimates of quantity and cost of stone pitching work/ pond lining and bund compaction/consolidation
- Screen for estimates of materials and cost of inlet structure (Pipe culvert)
- Screen for estimates of materials and cost of outlet structure/ waste weir (Straight drop structure).

In the developed software, the provision is made to use in built database of basic rates of schedules (BSR) for Delhi or can directly input materials costs by the user for calculating the cost of different kind of materials used in excavation and construction of farm pond and associated structures based on DSR for the year 2007.

The inputs for the sub-screen for estimates of excavation/ earthwork volume and cost for WH pond, include dimensions of the pond at three depth levels i.e. at bottom of pond, at ground surface and at top of the bund, dimensions of the bund /earthen embankment pond at three depth levels i.e. at bottom of pond, at ground surface and at top of the bund and estimation of total cost of pond including structures.

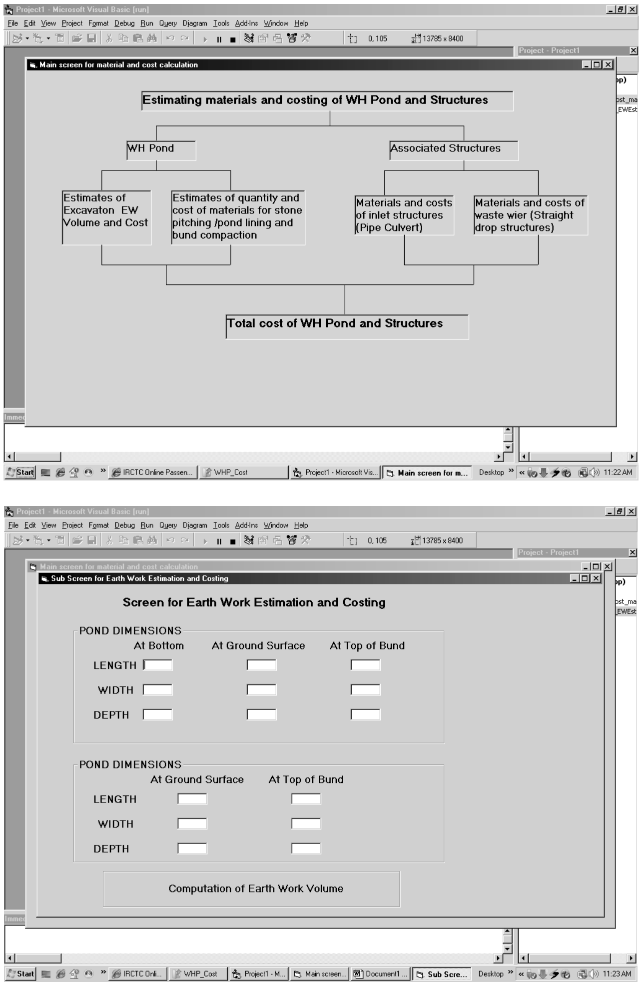


Fig. 8. Main screens for materials and cost estimation for pond and associated structure

3. RESULTS AND DISCUSSION

Hydrologic design module of software was calibrated and validated by comparing the software designs values of hydrologic parameters (rainfalls, runoff volumes and peak flow rates of return periods for Bhopal district with the standard design procedure values obtained.

3.1 Hydrologic Design Module

The software design values of hydrological parameters exactly matched with the calculated parameter values using standard design procedures. Test results are given in Table 5.

3.2 Hydraulic Design Module

Hydraulic design module was tested by comparing software design values of pond designs with standard design procedure values obtained for the developed water harvesting pond of 5.0 ha–m storage capacity having catchment area of 20 hectare (ha) and 8 ha irrigated command area. The procedural steps followed for design of pond are given Fig. 9. The software design values of hydraulic parameters (i.e. Pond capacity, pond dimensions at top and bottom) exactly matched with the calculated parameter values using standard design procedures. Test results are shown in Table 6.

The developed software was used for creating database of hydrologic design parameters of water harvesting pond and inlet/ outlet structures for ten identified districts namely Bhopal, Chhindwara, Datia, Dhar, Guna, Hoshangabad, Indore, Jabalpur, Khandawa and Raisen of Madhya Pradesh state of India. The software uses inbuilt data base of water requirement of main field crops and vegetables grown in identified districts.

Table 6. Comparison of hydraulic values (pond storage capacity and pond dimensions for square shape) of Bhopal district

Parameter	Software output	Calculated output
Capacity of pond (ha-m)	4.99	5.00
Top length (m)	132.0	132.10
Top width (m)	132.0	132.10
Bottom length	126.0	126.10
Bottom width	126.0	126.10
Depth of pond (m)	3.0	3.0

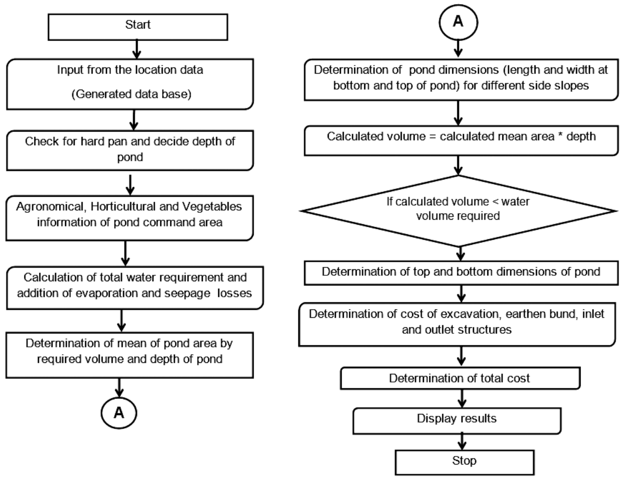


Fig. 9. Flow chart for design of pond

4. CONCLUSIONS

Software for the design of water harvesting pond and associated structures has been developed to make the designing task easy and simple. The software is developed using Visual Basic as front end and Microsoft Access as back end. The software has four basic modules – hydrologic design, hydraulic design, structural design and estimation of materials and costs of water harvesting structures. Hydrologic design

Table 5. Comparison of hydrologic parameters values of Bhopal district for different recurrence intervals

RI (yr)	Average annual rainfall (mm)		Annual runoff volume (mm)		Peak flow rate(m^3/s) for 25 years return period		
	Software output	Calculated output	Software output	Calculated output	Catchment area (ha)	Software output	Calculated output
1	1010.2	1009.8	322.7	322.4	1	0.228	0.230
5	1331.7	1331.4	577.2	577.0	5	0.834	0.831
10	1484.5	1484.0	740.5	740.0	10	2.000	2.012
20	1623.9	1623.2	858.8	850.0	20	3.700	3.716
25	1666.9	1666.2	946.6	946.9	25	4.420	4.419

module consists of three sub-modules. The software uses inbuilt database for different variables of formulae/ equations used in runoff and peak flow estimation for identified districts of Madhya Pradesh (MP**),** India. This software has been supported with database that contains data of 10 locations all over Madhya Pradesh State in India to make the design location specific. The software is armed with database addition and editing facility. The software has been tested at developer's level. Results obtained using software were compared with on-paper calculation and the results were found satisfactory. Pond design software has lead to the simplification of the design of water harvesting pond and associated structures is achieved to an extent that field officers and farmers can design those structures in their respective locations with easily and readily available information. The developed software can be used for creation of database of design parameters needed for design of water harvesting pond and associated structures as well as for their designs in Vertisols as well as other soil types. The developed database of design parameters needed for design of water harvesting pond and associated structures in vertisols of identified districts of Madhya Pradesh, may be used for designing the various soil and water conservation measures in Vertisols.

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