International Journal of Chemical Studies

P-ISSN: 2349–8528
E-ISSN: 2321–4902
www.chemijournal.com
IJCS 2020; 8(3): 1266-1273

Received: 20-03-2020
Accepted: 22-04-2020

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Evaluation and planning of existing drainage project for reclamation of waterlogged area: a case study

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DOI: https://doi.org/10.22271/chemi.2020.v8.i3q.9375

Abstract
Due to the flat topography and poor drainage condition, major parts of the Mahanadi delta command suffer from waterlogging problems. The sustainability of farm operations are highly affected by spatial and temporal rainfall variability. Thus, estimation of drainage design layout and identification of vulnerable area for waterlogging is the most vital operation for achieving maximum yield of paddy in cultivated land. This research investigation aimed to achieve an optimum level of soil moisture in the study area so that the yield of crops could be enhanced. Probability analysis of 25 years daily rainfall data was done to evaluate the appropriate drainage coefficient and runoff. Drainage coefficient for the study area was estimated to be 35.50 mm/day by SCS-Curve Number (CN) method, which was adopted for the design of surface drainage system with the 7 consecutive day storm and 10-year return period. The design discharge and peak discharge were evaluated to be 0.43 m^3/s by SCS-CN method and 4.92 m^3/s by the rational formula respectively, which were used for the design of the channel and the outlet structure, respectively. Standard procedures were adopted for the design of the channel as well as dimensions of the broad-crested drop spillway as outlet structure, respectively. The benefit-cost ratio of the new designed drainage system was found to be 2.48, which proved the new drainage system to be more efficient than the existing design.

Keywords: Consecutive days; annual maximum rainfall; drainage coefficient; waterlogging

Introduction

Now-a-days, various areas in the world have faced waterlogging and salinity problems, which are intensified by a myriad of factors including use of wastewaters for irrigation, unsuitable cropping pattern, torrential rains and floods, high precipitation in humid regions, lack of sufficient drainage, uncontrolled drainage, lack of adequate knowledge, wrong management decisions, very poor construction and rehabilitation rates of drainage systems, surplus irrigation water and canal seepage in the irrigated lands, increase of irrigation systems without paying any attention to their adverse impacts on soil and quality of water resources, etc. One effective way to reduce waterlogging and salinity problems is drainage. It is necessary to do a comprehensive study on previous works to arouse awareness of drainage, waterlogging, and salinity and to avoid trial and error policies in these fields. Drainage is the process to remove excess water from the soil by artificial or natural means. Waterlogging in irrigated regions may result in excess soil salinity, i.e., the accumulation of salts in the plant root zone. India covers 147.75 mha areas under different soil degradation classes explained by the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP). Under these categories, salt-affected soils spread in 6.73 mha areas and waterlogged in 6.41 mha areas (including 1.66 mha surface ponding and 4.75 mha subsurface waterlogging) (Anonymous, 2010) [2]. Bihar, Maharashtra, Gujarat, Uttar Pradesh, Odisha, West Bengal, Punjab, Tamil Nadu, Andhra Pradesh, Haryana, Kerala, Rajasthan and few other states of the country are experiencing more problems of water logging and salinity (Anonymous, 2009) [1].

Agricultural drainage is done mainly either by providing adequate surface or subsurface drainage system. Plant roots require a favourable environment to extract the nutrients and water from the soil to meet the plant's requirement. Excess water or high salt concentration in the root zone or at the land surface does not allow the plant roots to function normally. In the extreme case of water logging and salinity, the seed may not germinate and the plants may wilt permanently. Agricultural land drainage is both a preventive and a curative measure for the prevention of physical and chemical degradation of soil and for the reclamation of the already degraded lands.

In coastal areas of Odisha, waterlogging is the major land degradation problem. Waterlogging is mainly created by high rainfall and poor surface drainage. The coastal area being a flat land with a slope less than 0.02 percent does not permit easy drainage. Poor drainage conditions thus have developed water logging either due to surface ponding or rising of groundwater table owing to excess inflow as compared to outflow. The waterlogging affects the productivity and fertility of land and thus leads to the reduction in crop yield in these areas (Anonymous, 2010) [2]. Although it is a recurring phenomenon throughout the coastal Odisha, improper design of surface drainage system in Mahanadi delta is attributed to be the main reason for waterlogging leading to considerable crop damage and economic loss (Paul *et al*., 2014) [9]. In addition, other reasons responsible for waterlogging are seepage from unlined canals, damaged lined canals, impeded natural drainage due to canal network/roads, under-utilization of groundwater for irrigation, internal flow of subsurface water and poor water management (Chitale, 1991) [5]. Out of 0.0255 mha Gross Command Area in Mahanadi delta stage II, 0.0136 mha is Cultural Command Area and 56,000 ha area is affected by waterlogging due to poor drainage (Anonymous, 2011) [3]. Efforts are, therefore, needed to develop a suitable surface drainage system in this area to reduce the severity of waterlogging. The design of an economic and efficient surface drainage system depends on the selection of a proper drainage coefficient (Rao and Dhruvanarayan, 1979) [10].

In the present study investigations were done to evaluate the existing drainage system and plan a more efficient and economic drainage design in Mahanadi Delta command.

Materials and methods

Study area

The study area is located at Pipili block of Puri district, Odisha. It encompassed within the geographical coordinates of 20º 08′ 43.04 North latitude and 85º 50′ 26.89 East longitude. It is situated at a distance of 45 km from Command Area Development (CAD) sub-division, Puri. Figure 1 shows the location map of the study area. An area of 104.00 ha is facing acute drainage congestion due to excess runoff and seepage water from irrigation canal of Delang distributary resulting in waterlogged conditions in surrounding villages namely, Matiapada, Gobindpur, Siula and Aruha. For this purpose 1050.00 m of an earthen drainage channel was constructed by the CAD organisation, Govt. of Odisha in the year 2014-15 for reclamation of the drainage area.

Present canal system

The field visit and personal interview process with villagers reveals that though the existing drain has given considerable relief to the waterlogging situation, there still exists drainage congestion. During field inspection, it is observed that there has been a considerable amount of silt deposition in the drainage channel with weed growth, not only along the drain but also at the outlet area and there is no outlet structure for smooth discharge of water. This results in the creation of water congestion at the head reach and there is no proper disposal of drainage water. It is expected that if the existing channel will not be maintained and cleared properly from time to time, the total system will be completely defunct due to silting and growth of weed.

Due to the existing drainage problem there is approximately 0.50 to 0.75 m of standing water during the months of July and August in the *kharif* season. Therefore, rice transplantation is shifted by 1.5 months. This reduces the yield of rice and hampers in operation of farm machinery in fields. The reduction in rice yield and the problem for farm machinery operation is lowering the net income of farmers.

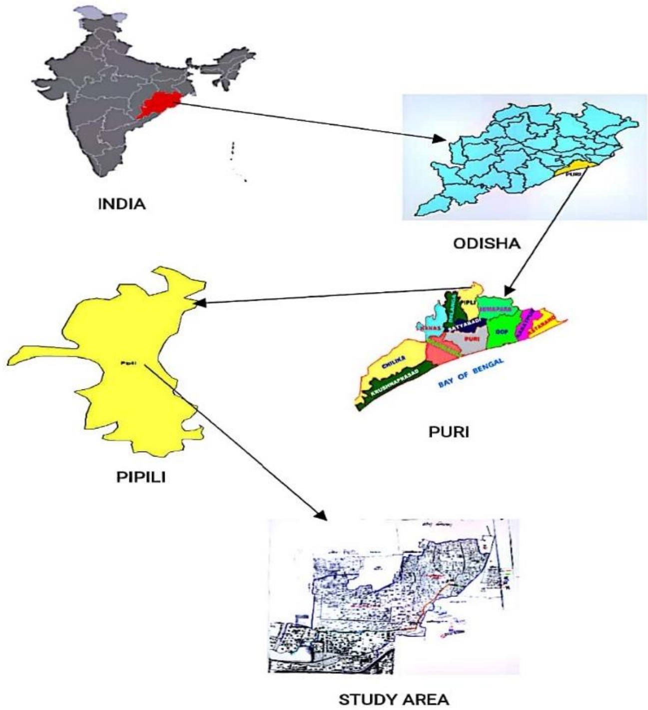


Fig 1: Location map of the study area

Weather data

The daily rainfall data for a period of 25 years starting from 1992 to 2016 was collected from the nearest rain gauge station at Pipili block headquarters. The average annual rainfall of study area is 1410 mm. The highest one-day rainfall observed was 194 mm (dated 18th August 1994). The rainfall data are analyzed for one, two, three, four, five, six, seven consecutive day's storm (Figure 2). The relationship between depth, duration and frequency has been established (Figure 3) which was helpful in deciding the design rainfall for any number of consecutive days from one to seven and for any recurrence interval. For rice crop, crop tolerance period and a maximum depth of submergence were assumed as 7 days and 150 mm, respectively. The probability approach was used to estimate the design rainfall in order to predict the design runoff. It is a universally accepted fact that higher the design rainfall, higher is the cost of the project and lower is the chance of failure. An average failure in agricultural production once in 10 years is generally accepted and hence, the recurrence interval was fixed at 10 years. The 7 days consecutive rainfall for 10 years return period was estimated as 355 mm which was used for runoff estimation using curve number method.

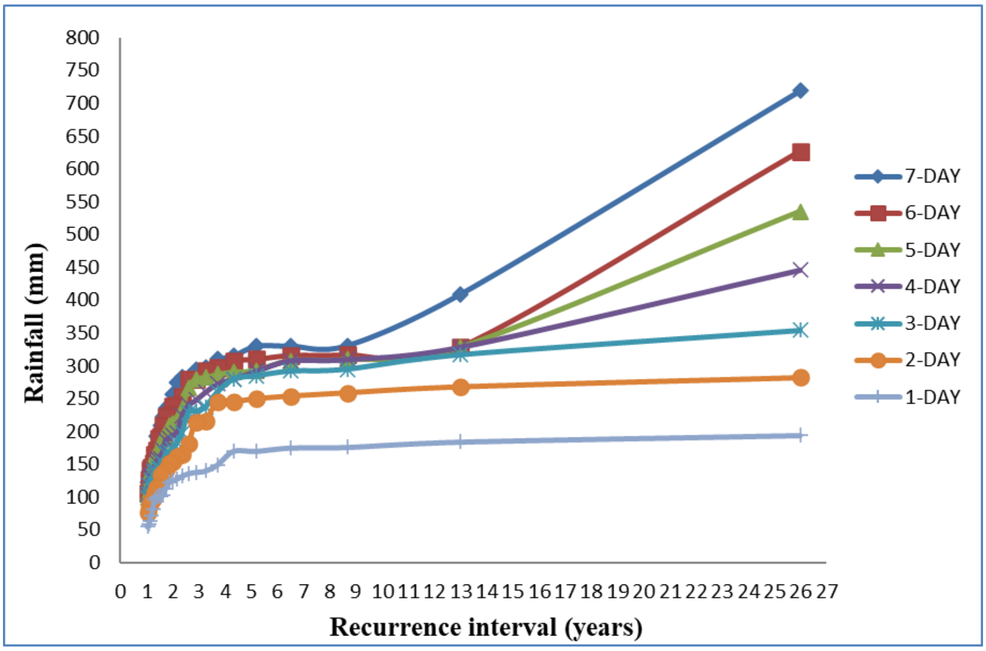


Fig 2: Rainfall depth for various recurrence intervals and for different consecutive days

The daily evaporation data of 16 years (2001-2016) was collected from USWB, Class A evaporation pan of meteorological observatory central farm, Orissa University of Agriculture and Technology which is in the vicinity of study area. From these data the mean monthly and mean daily values were found out for each month. First, the pan evaporation data "EP" was multiplied by pan coefficient for class A USA pan for different months (Doorenbos and Pruit, 1977) [6], which gives the potential evapotranspiration "ET_0". Crop evapotranspiration for paddy is calculated by multiplying "ET_0" by the crop coefficient (K_c) for paddy. The standard crop coefficient for kharif paddy as given by Doorenbos and Pruit (1977) [6] for different growth stages was used for calculation of evapotranspiration of paddy for different stages and months from which mean evapotranspiration value was evaluated.

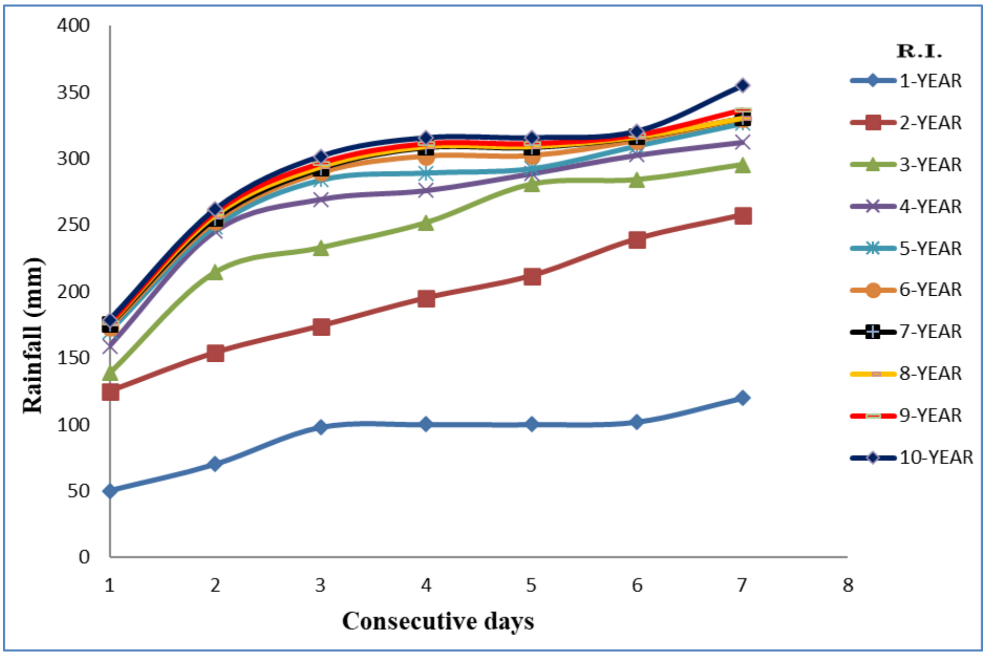


Fig 3: Depth, duration and frequency curve of rainfall at Pipili

Soil textural classification

Soil samples collected from Matiapada and surrounding villages were analyzed by the hydrometer method. From the USDA textural classification (According to the percentage of sand, silt and clay found in the samples) the surface texture of major area was observed to be loam. The analysis shows that the clay content of the soil ranges from 13.8 to 23.8 per cent, silt 17.2 to 21.2 per cent and sand 55 to 69 per cent and hence soils of the study area were classified as loamy soil.

Estimation of drainage coefficient and runoff rate

Curve Number method

This method is used to compute the runoff discharge in terms of depth. It is suitable for small agricultural watersheds and specially developed for flat areas having slopes of 0-5 per cent. It is known as Hydrologic Soil Cover Complex (SCS) method or USDA-Curve Number method or SCS-Curve Number method or simply CN method. The term Hydrologic Soil Cover Complex is adopted as it considers the effect of soil type or group, soil wetness or antecedent moisture condition, land coverage by vegetation and nature of cultivation practices, etc.

Direct Runoff or Surface Runoff, $Q = \frac{(P-I_a)^2}{(P-I_a+S)}$ (1)

Where, I_a = Initial abstraction from rain, mm, P = Rainfall depth, mm, and S = Maximum or potential abstraction, mm.
For the present project, I_a = 0.3S is used

So, $Q = \frac{(P - 0.3S)^2}{(P - 0.3S + S)}$

Where, S = 25400/CN – 254

This depth of runoff is to be removed within a period of 7 days.

Estimation of peak discharge
Rational formula
The rational formula is the most widely used procedure to estimate the peak rate of runoff at the outlet of the watershed. The peak discharge is estimated as:

$$Q = \frac{C*I*A}{360} \quad (2)$$

Where, Q = Peak runoff rate, $m^3.s^{-1}$, C = Runoff co-efficient (taken as 0.4 for the study area),
I = Rainfall intensity for a duration equal to time of concentration and for a particular return period, $cm.h^{-1}$, and A = Watershed area, ha.
The time of concentration 'Tc' is the most important factor to decide the rainfall intensity 'I' in the formula which is given by Kirpitch formula as:

$$T_c = 0.0195 * L^{0.77} * S^{-0.385} \quad (3)$$

Where, T_c = Time of concentration, min, L = Maximum length of water flow (from most remote point to the outlet), calculated as 1650 m for the study area, and S = Average slope of watershed land (calculated 0.0005 $m.m^{-1}$ for the study area).
In order to determine the rainfall intensity for the estimated T_c, 1 h rainfall maps of India for 25-year (for outfall structure design) return period were used, and intensity conversion graph was obtained using standard procedure (Panigrahi, 2011) [8].
The Rational method gives a very high value of drainage coefficient for drainage design. This is because the formula assumes a uniform distribution of rainfall intensity over the entire catchment area which does not occur in the real situation. Rather rainfall occurs with high intensity and short durations over small areas and never becomes uniform. Such a high value of peak discharge is not advisable for structural design. Hence a 60% value of the peak discharge as calculated by rational formula has been taken for the design of the outlet structure.
The drainage channel is designed as per the design discharge rate which is less than the peak flow rate. Application of uniform flow formula and lesser flow rate may result in temporary overtopping of the channel and water logging of adjoining agricultural land. However, this is permissible, as crops have certain inbuilt mechanism to withstand flooding up to certain durations. But on the other hand, designing with peak flow rate would result in a cross-section of a channel, too large to accommodate, consume valuable agricultural land, and increase the cost of construction. However, the outlet structure should be designed as per the peak discharge rate, failure of which may create more serious problem than the reduction in crop yield due to overtopping (Bhattacharya and Michael, 2003) [4].

Design of drainage channel
Velocity of flow
A drainage channel is usually unlined and it carries sediment loaded runoff water. Hence the design should be such that neither there should be too much scouring due to higher velocity nor too much silting due to lower velocity. This type of non-silting and non-scouring velocity is determined by Manning's formula as:

$$V = \frac{1}{n} \times R^{2/3} \times S^{1/2} \quad (4)$$

Where, V = Mean velocity of flow in channel (m/sec), R = Hydraulic radius of flow (m), A = Area of flow (m^2), P = Wetted perimeter (m), S = Channel bed slope (fraction), and n = Manning's roughness coefficient, taken as 0.035.

Channel cross section and slopes
A trapezoidal cross section was selected keeping in mind the stability and constructional case. A steep bed slope causes high velocity of flow and erosion whereas a mild slope results in silt deposit in the bed. A bed slope of 0.20% is considered for the channel as for loam soil the bed slope ranges between 0.2- 0.4%. The side slope is selected based on soil texture.

Computation of design dimensions
The dimensions are to be determined for the most efficient hydraulic trapezoidal section in which

Base width, $b = 2d \tan \Theta/2$ (5)

Where, d = Depth of channel, Ɵ = Angle between sloping side and horizontal.
For trapezoidal section,

Cross sectional area, $A = b\,d + z\,d^2$ (6)
Wetted perimeter, $P = b + 2d\sqrt{(z2 + 1)}$ (7)
Hydraulic radius, R = A / P (8)

Using the known values of design discharge (Q), the dimensions were determined for the designed cross section of field drain.

Design of outlet structure
An outlet structure is necessary at the junction point of the field drain and the trunk drain for final disposal of runoff. The design of such structure is made as per the peak discharge value obtained by rational formula and for a return period of 25years. In the present project, a broad crested drop structure is selected for the stability of the drain section and for safe final disposal of runoff. The computations of structural components are made by suitable design formulae.

Economic analysis of the drainage system
The estimate of costs for different components of the work has been prepared. The benefits of the project comprised of

the goods and services, the production of which is due to the project or the damage presented.

Annual cost

The annual cost of a drainage system conveniently classified under the following heads:

a) Life span of drainage system,
b) Initial capital investments made for the installation of drainage system,
c) Interest of capital invested,
d) Maintenance operation and management cost.

$$\text{Annual Cost} = \frac{\text{Capital invested+Interest of Capital Invested+Maitenance Cost}}{\text{Life Span of Project}} \quad (9)$$

Annual benefit

Annual benefit is to be calculated from the production increase annually.

Benefit- cost ratio

It is the ratio between annual benefit and annual cost invested in for installing drainage system. It is expressed as

$$\text{Benefit Cost Ratio} = \frac{\text{Annual Benefit}}{\text{Annual Cost}} \quad (10)$$

Comparative study

A comparative study of the existing and the new design of the drainage line has been made.

Results and discussion

Estimation of drainage coefficient and runoff rate

SCS-Curve number method

The project area falls into the AMC–III category and soil group–B. Under such conditions, the curve number value is worked out to 98 using the conversion factor for AMC–III. The potential maximum retention (S) is estimated at 5.18 mm, whereas the 7-day consecutive rainfall for 10-year return period is estimated to be 355 mm. Deducting the storage depth of 100 mm assigned for paddy crop, the rainfall depth (P) is estimated at 255 mm. Further, the direct runoff depth (Q) is estimated at 248.37 mm whereas the drainage coefficient (dc) is estimated at 35.50 mm $day^{-1.}$

Rational method

For the study area, the time of concentration (Tc) was estimated to be 109.25 min. For outlet design, 25- year return period map was considered. Accordingly, 1 h rainfall for the given location was obtained as 100 mm h^{-1}. From the conversion graph, the desired rainfall intensity for the duration equal to the time of concentration of 109.25 min was determined at 7.1 cm h^{-1}. Hence, peak discharge (Q_p) was estimated at 8.20 $m^3 s^{-1.}$

Design of drainage channel

The design discharge of the field drain (Q) for the project area is taken as 0.43 cumec. A trapezoidal section was adopted in order to have a suitable drainage channel. The bed slope of the channel is taken as 0.2%. The side slopes for loam soil are taken as 1.5:1 (Horizontal: Vertical) i.e. z = 1.5. So, tan Ɵ = 1/1.5, therefore, Ɵ = 33.70^0 and Ɵ /2 = 16.85^0

For the best hydraulic section in a trapezoidal channel, the design parameters were worked out using equations 5, 6, 7 and 8 as mentioned above in computation of design dimensions:

Base width, $b = 2d \tan \Theta/2 = 2d \tan(16.85) = 0.606\, d$ (11)

Area, $A = bd + zd^2 = 2.106\, d^2$ (12)

Wetted perimeter, $P = b + 2d\sqrt{(z^2 + 1)}$
$= 0.606\, d + 2d\sqrt{(1.5^2 + 1)} = 4.212\, d$ (13)

Hydraulic radius, $R = A/P = 0.5\, d$ (14)

Hence, using equation 4, velocity by Manning's formula is given as:

$V = 1/n\, (R)^{2/3}\, (S)^{½}$

Where, n = 0.035 and S = 0.002

Now design discharge,

$Q = A \times V = 2.106\, d^2 \times 1/0.035 \times (0.5\, d)^{2/3} \times (0.002)^{1/2}$
$= 0.805\, d^{8/3}$ (15)

Putting Q = 0.43 cumec and solving for d and b

$d = (0.43/0.805)^{3/8} = 0.60$ m

b = 0.606 d = 0.35 m

Free board = 0.10 m and berms = 0.15 m were provided to meet the situation of overtopping of channel.

Hence, depth, d = 0.70 m,

Base width, b = 0.35 m,

Top width, t = 2.45 m.

The design cross section of the drainage channel is presented in Figure 4. The design cross section of the existing drainage channel is presented in Figure 5.

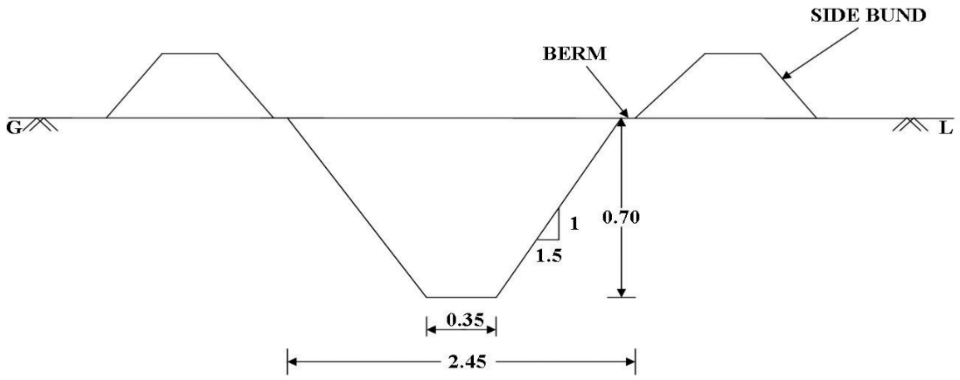
Velocity check

The velocity of flow should remain within the safe permissible limit to find a non-scouring and non-silting condition.

Area, $A = 2.106\, d^2 = 2.106\, (0.70)^2 = 1.03\, m^2$

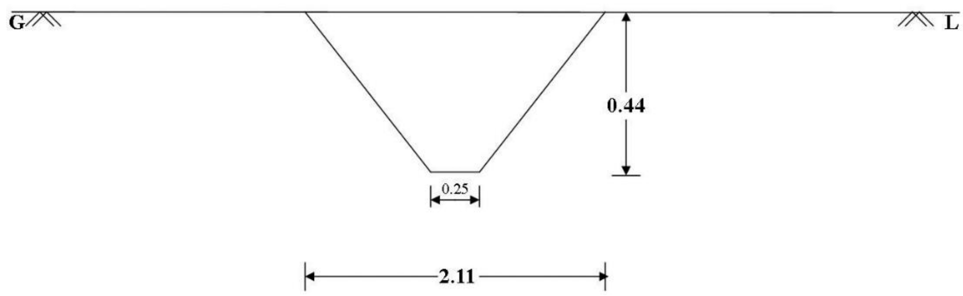
Velocity, V = Q/A = 0.43/1.03 = 0.42 m/ sec

As, V < 0.60 m/sec for loam soil, so the design is considered safe.



(All dimensions are in meter)

Fig 4: Cross-sectional view of design drainage channel



(All dimensions are in meter)

Fig 5: Cross-sectional view of existing drainage channel

Comparative study

A comparative study is done between the existing and the new design of the drainage line and the results are tabulated below (Table 1).

Table 1: Comparison of existing drain with the design drain

S. No.	Existing design	New design
1	Base width (b) = 0.25 m	Base width (b) = 0.35 m
2	Top width (T) = 2.11 m	Top width (T) = 2.45 m
3	Depth of channel (d) = 0.44 m	Depth of channel (d) = 0.70 m

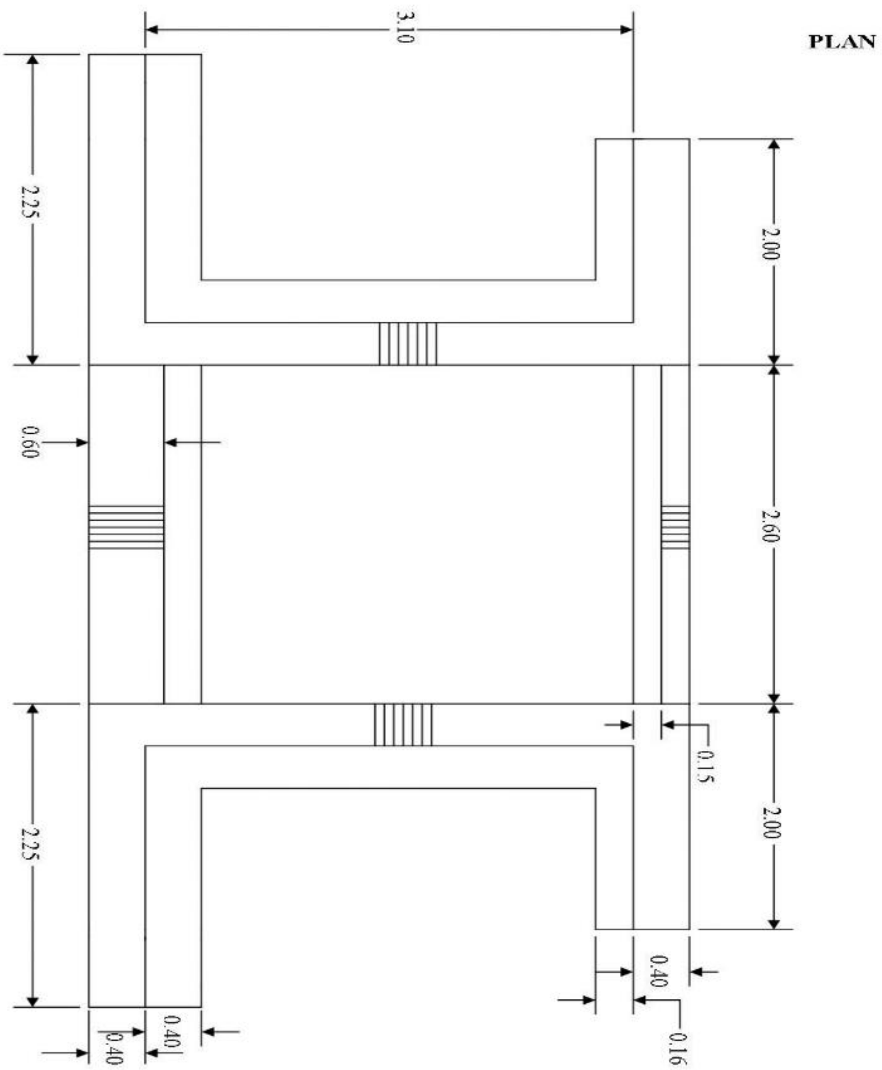
From the comparison, it is observed that the existing drainage dimensions are less than the new designed dimensions which shows that the former is not sufficient enough to carry the design runoff which therefore creating drainage congestion in study area.

Design of outlet structure

The design dimensions of the drop spillway were calculated as per standard procedures (Murty and Jha, 2009) [7], and presented in Table 2 and Figure 6.

Table 2: Design dimensions for different components of outlet structure

Head wall		**End sill**		**Head wall Extension**	
Length	2.60 m	*Height*	0.35 m	Length	2.25 m
Height	1.25 m	Top Width	0.15 m	Height	2.40 m
Top width	0.60 m	Bottom width	0.30 m	Top width	0.40 m
Bottom width	0.80 m	Inward slope	1:1	Bottom width	0.80 m
Cut-off		**Side wall**		**Wing wall**	
Depth at u/s	0.55 m	Length	3.10 m	Length	2.00 m
Depth at d/s	0.65 m	Height	2.40 m at HWE & 0.80 m at WW	Height	0.80 m
		Top width	0.40 m	Top width	0.40 m
		Bottom width	0.80 m	Bottom width	0.80 m



(All dimensions are in meter)

Fig 6: Plan of outlet structure

Estimation of cost

The estimate for the drainage channel has been prepared following Schedule of Rate 2014, Government of Odisha.

Benefit-Cost ratio

Estimated project cost: Rs 3, 68, 779.00
Benefitted area: 104 ha
Life span of the project: 10 years
Depreciated annual project cost: Rs 36,877.90
Annual interest on project investment @ 14%: Rs 51, 629.06
Annual maintenance @ 5%: Rs 18, 438.95
Total annual investment: Rs 1, 06, 945.91
The net annual project return including both pre-project and post-project cost estimates are given in Table 3.

Pre-project cost estimate

Table 3: Net annual project return

Crop season	Crop	Area(ha)	Yield(q/ha)	Selling Price (Rs/q)	Cost of cultivation (Rs/ha)	Gross income (Rs)	Net income (Rs)
Kharif	Paddy	65	24	1400	30000	2184000	234000
Rabi	Pulses	85	5	5000	20000	2125000	425000
Yearly Net Profit Rs 6, 59, 000							

Post- project cost estimate

Crop season	Crop	Area(ha)	Yield(q/ha)	Selling Price (Rs/q)	Cost of cultivation (Rs/ha)	Gross income (Rs)	Net income (Rs)
Kharif	Paddy	90	25	1400	30000	3150000	450000
Rabi	Pulses	95	5	5000	20000	2375000	475000
Yearly Net Profit Rs 9, 25, 000							

Using Equation 10,

$$\text{Benefit Cost Ratio} = \frac{\text{Annual Benefit}}{\text{Annual Cost}}$$

= 2, 66, 000/1, 06,945.91
= 2.48: 1

The value is greater than 1: 1
Hence the project (new design) is feasible.

Conclusions

From the rainfall analysis, the average annual rainfall was observed to be 1410 mm. The highest one-day rainfall was found to be 194 mm. The maximum 7 days consecutive rainfall at 10 years return period was evaluated to 355mm, which was used for calculation of drainage coefficient. Drainage coefficient was found to be 35.50 mm/day by SCS-Curve Number method for the study area. Drainage coefficient of 35.50 mm/day computed by Curve Number method was adopted for the design of surface drainage system with the 7-day storm and 10-year return period. The design discharge and peak discharge were computed as 0.43 m^3/s by SCS-CN method and 4.92 m^3/s from the rational formula which are used for the design of the channel and the outlet structure, respectively. Standard procedures were adopted for the design of the channel and the broad-crested drop spillway was proposed as the outlet structure. The benefit-cost ratio of the project (new design) was estimated to be 2.48:1 indicating that the drainage project is highly feasible.

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