*Original Research Article*

A Multistage Optimization Approach for Cost-Effective Drip Irrigation Design

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ABSTRACT

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| This study presents an optimal design methodology for a drip irrigation system using a multistage optimization approach. The method determines the optimal diameter of lateral, manifold and mainline pipeline by minimizing the total annualized cost, which may include fixed costs, energy costs, or a combination of both. Frictional head loss in each pipeline segment is computed using the Darcy–Weisbach equation, ensuring accurate hydraulic evaluation across the varying sections. The core input to the optimization model consists of the annual costs associated with all available single-diameter pipe alternatives, enabling systematic selection of the most cost-effective pipe configuration along the length of the multi-outlet system. Among all the combinations, the most cost-effective hydraulically feasible configuration is observed with 20 mm laterals, 40 mm manifolds, and 63 mm mainlines. This approach achieves a total annual cost of ₹12215 (annual fixed cost = 8270 and Energy cost = 3945) and a cost per unit area of ₹1.82/m², marking it as the optimal solution balancing both hydraulic and economic performance.  |

***Keywords:*** *Multistage Optimization, Drip Irrigation, Optimal Design, Double Manifold Layout, Optimization models, Capital cost, Energy cost.*

1. INTRODUCTION

Water scarcity and rising energy costs have posed significant challenges to the sustainability of irrigated agriculture, particularly in arid and semi-arid regions (Priyan, 2021; Vishwakarma *et al.,* 2023). Drip irrigation, a pressurized micro-irrigation method, has emerged as a promising solution to enhance water-use efficiency by delivering water directly to the plant root zone with minimal losses (Patel *et al.,* 2023). However, the effectiveness of drip systems largely depends on their hydraulic design and economic feasibility (Baiamonte andPalermo, 2025; Wang *et al.,* 2025). Improper selection of pipe sizes and system layout can lead to excessive pressure variation, high energy consumption, and increased installation costs, ultimately compromising uniformity and system longevity (Seyedzadeh *et al.,* 2021; Sithole *et al.,* 2023).

Traditionally, the design of drip irrigation networks has relied on heuristic or trial-and-error approaches, which are often inefficient for large-scale systems with multiple pipe segments (Mahar and Singh, 2014). Enumeration-based optimization methods, while exhaustive and capable of identifying global optima, become computationally impractical as the number of decision variables increases. Furthermore, these methods do not easily adapt to real-time decision-making in dynamic field conditions. A comprehensive overview of optimal pipeline design for water supply systems can be found in the works of Mays and Tung (1992), Lansey and Mays (2000), and Bhave (2003). Notably, Lansey and Awumah (1994) applied dynamic programming to optimize pump operation schedules in water distribution networks, with the objective of minimizing energy consumption costs.

The capital cost associated with discrete pipe sizes, along with the operating characteristics of pumps and the energy cost required to overcome pipe friction, exhibit inherent nonlinear behavior (Singh and Mahar, 2003; Mahar and Singh, 2014; Pandey *et al.,* 2020; Sithole *et al.,* 2023). Consequently, a nonlinear programming model is more suitable for selecting the optimal pipe sizes, as it can account for the replacement cost of pumps and their performance characteristics in relation to the required flow rate and pressure head (Sithole *et al.,* 2023). This approach allows for a more accurate and realistic representation of system behavior, leading to cost-effective and hydraulically feasible design solutions.

To address these limitations, the present study proposes a multistage programming approach for the optimal hydraulic and economic design of drip irrigation systems. The method involves decomposing the system into sequential hydraulic segments—laterals, manifolds, submains, and mainlines—and determining the optimal pipe diameter for each segment by minimizing the total annual cost. This cost includes both the annualized fixed cost (material and installation based on pipe length and diameter) and the energy cost, calculated from the hydraulic gradient across each segment. Pressure head and discharge uniformity constraints are also integrated to ensure hydraulic feasibility.

To achieve the objective of this research, a widely used field layouts: Central Manifold Layout (CML) layout was analyzed using different pipe diameter combinations, evaluating hydraulic performance parameters (pressure head, head loss, and discharge deviation) and economic metrics (fixed cost, energy cost, total cost, and cost per unit area). The primary objective of this optimization model is to identify the optimal combination of pipe diameter and pump operation parameters that result in the minimum total annual cost of the system.

2. methodology

The total cost of a pumped water supply system typically comprises the capital costs of the pipeline and pumping unit, their respective replacement costs, the energy cost required to operate the pump, and maintenance and repair expenses associated with system components. Maintenance and repair costs are often estimated as a fixed percentage of the capital cost or excluded from detailed analysis, as their relative impact remains consistent across alternative component selections. Some studies have employed techno-economic analyses that incorporate comprehensive cost assessments, including repair and replacement of failure-prone components within the network. Bhave (2003) outlined several economic evaluation methods for water supply systems, including the present worth method, annual cost method, benefit-cost ratio method, and rate of return method. In the present study, the annual cost method—as described by James and Lee (1971)—is adopted for life-cycle cost analysis, enabling a systematic comparison of design alternatives based on both capital and operational cost components.

**2.1 fixed cost**

**2.1.1 Emitter cost**

The number of emitting device (*Ne*) is obtained by dividing the length of the lateral line by the spacing between emitters along the row. The annual fixed cost of the emitting device is calculated using the following expression:

|  |  |
| --- | --- |
|  | (1) |

where *F1* = annual fixed cost of the emitting devices (₹); *Ie*​ = initial cost per emitter (₹/unit); = total number of emitting devices required; CRF = capital recovery factor (dimensionless), accounting for interest rate and emitter lifespan which can be calculated as:

|  |  |
| --- | --- |
|  | (2) |

where = capital recovery factor; = number of years in the life cycle; = decimal equivalent annual interest rate.

**2.1.2 Pipeline Cost**

The yearly fixed cost for a pipe segment with a diameter of "d" remains consistent across all segments with evenly spaced outlets. The annual fixed cost of the "d" diameter pipe per unit length is expressed by Eq.:

|  |  |
| --- | --- |
|  | (3) |

where *F2​* = Annual fixed cost of the pipeline (₹); *IP*​ = initial capital cost of the pipe (₹/m) for the given diameter; *L* = length of the pipe segment (m).

**2.1.3 Cost of pumping unit**

The capital cost is primarily influenced by the required discharge and pressure head of the system (Pandey *et al.,* 2020). According to Bhave (2003), the capital cost of a pumping unit can be estimated using the following Eq.:

|  |  |
| --- | --- |
|  | (4) |

Where *Cp* ​ = capital cost of the pump (₹); *Q* = discharge of the pump (litres per second); *HTotal* = total head required at the pump (m); *Cu*​ = cost of the pumping unit = 6000 ₹/kW (Bhave, 2003); *η* = overall efficiency of the pump (decimal). The annual fixed cost of the pump is calculated using the capital recovery factor (CRF):

|  |  |
| --- | --- |
|  | (5) |

Where = annual fixed cost of the pump (₹).

**2.2 Energy Cost**

The annual energy cost associated with overcoming frictional head loss in the pumping main can be calculated using the formulation provided by Mahar and Singh (2001). This method accounts for the energy required to maintain the desired flow rate against the hydraulic resistance of the pipeline and is integral to accurately estimating the operational costs of pressurized irrigation or water supply systems. The annual energy cost can be estimate using the following Eq.:

|  |  |
| --- | --- |
|  | (6) |

where, *EC* = annual energy cost of the to operate the system (₹); = total lateral discharge (lps); = number of annual working hours; = system head requirement (m); = energy cost (₹/kW/h); and = over all pump efficiency in %.

**2.2.1 System head**

The system head requirement can be calculated as:

|  |  |
| --- | --- |
|  | (7) |

where *hst* = static head (m); *hf* = frictional head loss in the total length of the pipe (m); and *hm* = the minor head loss (m). The value of hf can be calculated using the Hazen-Williams Eq. as:

|  |  |
| --- | --- |
|  | (8) |

where *J* = head loss – percent of pipe length; Δ*hf* = frictional head loss (m); *L* = length of the pipe line (m); *Q* = flow rate through the pipe line (m³/h); *C* = Hazen–Williams roughness coefficient (dimensionless); *D* = internal diameter of the lateral pipe (mm); *F* =unitless reduction factor for multiple outlets. The reduction factor *F* can be calculated using empirical Eq.

|  |  |
| --- | --- |
|  | (9) |

where *F* = dimensionless correction factor for frictional head loss due to multiple outlets; *Ne*​ = number of outlets along the pipe; *i* = index of the outlets (from 1 to *Ne*).

**2.2.2 Allowable pressure head variation**

If the allowable pressure variation within the subunit is limited to 20% of the average pressure head, then the permissible pressure head loss in the subunit (*ΔPs*) in drip irrigation can be expressed mathematically as:

|  |  |
| --- | --- |
|  | (10) |

where *ΔPs* = permissible pressure head loss in the subunit (m); = average system pressure (m).

The total allowable pressure difference with in the subunit is determined as *ΔPs*, the value of *ΔPs* must be satisfy the following relation:

|  |  |
| --- | --- |
|  | (11) |

where ​ = total permissible pressure variation within the subunit (m); *​* = pressure head variation along the lateral line; and ​ = pressure head variation along the manifold or submain line

The cumulative pressure losses in the lateral and manifold lines do not exceed the total allowable variation defined for maintaining emission uniformity. The allowable friction head loss along the lateral is estimated by:

|  |  |
| --- | --- |
|  | (12) |

where ​ = allowable friction head loss along the lateral (m); ​ = total allowable pressure variation within the subunit (m); and ​ = elevation difference along the lateral (m) (ZInlet - Zend); positive if the lateral slope is downward and negative if upward lateral slope.

This equation accounts for both frictional losses and elevation effects, ensuring that pressure variation remains within acceptable limits to maintain emission uniformity.

The allowable friction head loss along the manifold is estimated by:

|  |  |
| --- | --- |
|  | (13) |

where ​ = allowable friction head loss along the manifold (m); ​ = total allowable pressure variation within the subunit (m); ​ = elevation difference along the manifold (m) (*Z*Inlet - *Z*end); positive if the manifold slope is downward and negative if upward manifold slope.

**2.2.3 Pressure distribution**

Designating the nominal pressure by , the inlet pressure by and the far end pressure by , the pressure distribution and maximum pressure difference along the lateral are as follows:

|  |  |
| --- | --- |
|  | (14) |
|  | (15) |

where Δ*Hl* = total frictional head loss along the lateral line (m); Ze, Z1, and Z2 = elevations at the location of the emitter with nominal discharge, lateral inlet and lateral far end respectively (m).

The pressure distribution along the manifold is expressed as:

|  |  |
| --- | --- |
|  | (16) |
|  | (17) |

where ​ = pressure head at the inlet of the manifold (m); ​ = pressure head at the end of the manifold (m); Δ*Hm* = total frictional head loss along the manifold (m).

The similar can be used to pressure distribution in submain and mainline.

**2.3 Total annual cost**

The total annual cost of the complete drip irrigation system—including emitting device, the pipeline network (laterals, manifolds, submains, and mainline), and the pumping unit, can be expressed as:

|  |  |
| --- | --- |
|  | (18) |

where = total annual cost of the irrigation system (₹), including emitting devices, the entire pipeline network, and the pumping unit (e.g., electric motor).

**2.4 Optimization Model**

The cost functions associated with the pumping main and pump exhibit nonlinear behavior, as described by Eqs. (1), (3), (5), and (6). The optimal diameter of the lateral, manifold, submain and pumping main and the corresponding operating conditions of the pump that minimize the total system cost. The primary objective of this optimization model is to identify the optimal combination of pipe diameter and pump operation parameters that result in the minimum total annual cost of the system, as expressed in Eq. (18). This optimization is subject to constraints imposed by pump performance characteristics and system head requirements. The corresponding objective function can be formulated accordingly:

|  |  |
| --- | --- |
|  | (19) |

where is the minimum annual cost from point *i* (1) to the final point j (42), and is the cost from point *i* to point *j*.

3. Design Example and Discussion

**3.1 Design Example**

Design a subunit apple orchard under drip irrigation. The field is completely flat so that topography effects do not influence the design. The area are ten rows of trees per subunit, each 120 m long. The spacing of the tree is 4 m in the rows and 6 m between the rows. The two different layouts of lateral and manifold and mainline and pump location of system are shown in Figure 1. The selected drippers had the following characteristics:

Emitter discharge rate (*qe*) = 8 lph; average pressure (*Pe*) = 13 m; emitter exponent (*x*) = 0.48; one lateral per row with drippers every 1 m in the row, hence emitter spacing (*b*) = 1 m; lateral to lateral spacing = 6 m and plant to plant spacing (*net*) = 4 m. The lateral/manifold/submain/mainline cost and pump are given in methodology section 3.4. The data for the design problems are given below:

***Emitter and Pipe line data***

The emitter cost is 7.30 per nos for 8 lph. The data related to available pipe sizes with their corresponding cost are given in Table 1 and Table 2. The length of lateral, manifold and mainline are 60, 27 and 65 m respectively for layout 1. The Hazen-Williams formula used with Hazen-Williams friction coefficient *C* = 140.

***Life cycle cost analysis data***

The economic factors of emitters, pipes and pump are:

Estimated hours of operation per year = 1000 hr; decimal equivalent annual interest (*r*) = 0.10, number of years in life cycle (*y*) of emitter, pipe and pump are 8, 10 and 30 years, overall pump efficiency (*ƞ*) = 0.75 and electricity cost per unit 6.50 ₹/kWh.

**Table 1.** Jain Tough Hose-Twin-Line® Drip Polytube as per IS:12786.

|  |  |  |  |
| --- | --- | --- | --- |
| **Nominal outside diameter (mm)** | **Inside diameter (mm)** | **Minimum wall thickness (mm)** | **Cost (₹/m)** |
| 12 | 10.80 | 0.60 | 6.00 |
| 16 | 14.40 | 0.80 | 10.70 |
| 20 | 18.20 | 0.90 | 14.00 |
| 25 | 22.60 | 1.20 | 22.05 |
| 32 | 29.00 | 1.50 | 35.15 |

Nominal Diameter: 12 mm to 32 mm; Working Pressure: 2.0 kg/cm² to 4 kg/cm²

**Table 2.** PVC pipes of various nominal outside diameters and their corresponding minimum wall thickness under different pressure ratings (as per IS:4985), used in lateral lines, manifolds, submains, and mainlines in pressurized irrigation systems.

|  |  |  |  |
| --- | --- | --- | --- |
| **Nominal outside diameter (mm)** | **Minimum wall thickness (mm)** | **Inside Diameter (mm)** | **Cost (₹/m)** |
| 25 | 1.20 | 22.60 | 26.60 |
| 32 | 1.50 | 29.00 | 41.40 |
| 40 | 1.80 | 36.40 | 59.80 |
| 50 | 2.30 | 45.40 | 95.45 |
| 63 | 2.80 | 57.40 | 138.55 |
| 75 | 3.40 | 68.20 | 199.80 |
| 90 | 4.00 | 82.00 | 279.25 |
| 110 | 4.90 | 100.20 | 420.30 |
| 125 | 5.60 | 113.80 | 556.30 |
| 140 | 6.30 | 127.40 | 693.60 |

*Pressure Rating = 8 kg/cm²*

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**Figure 1. Central manifold layout (CML) of drip/ microsprinkler irrigation system.**

**3.2 Solution**

The given data were used to estimate the permissible head loss in the subunit and head loss in the subunit. The total head loss along the lateral *ΔHl* was 6.150 m, 1.515 m, 0.484 m, 0.169 m, and 0.050 m for the 12 mm, 16 mm, 20 mm, 25 mm, and 32 mm lateral size. The analysis of pressure variation revealed that laterals with diameters of 12 mm and 16 mm exceed the permissible head loss limit (*ΔHl* >*ΔHl* max), rendering them unsuitable for design. Conversely, the 20 mm, 25 mm, and 32 mm lateral options maintained acceptable pressure variations (*ΔHl* <*ΔHl* max) and are considered hydraulically feasible. The variation in head loss and its implications for lateral selection are illustrated in Figure 2. Pipe sizes 12 mm and 16 mm are infeasible due to excessive head loss, while sizes 20 mm, 25 mm, and 32 mm fall within the acceptable range for system performance.

Since, *ΔHl* is 6.150, 1.515, 0.484, 0.169 and 0.050 m then, we can adjust the *ΔHm* as *ΔHm* max = *Ps* - *ΔHl* (i.e., 2.6 - *ΔHl*) and shown in Figure 3. The *ΔHm* along half of the length of the manifold- from centre to the end. The results clearly indicate that smaller pipe diameters such as 25 mm and 32 mm result in excessive head losses (*ΔHm* = 9.378 m and 2.786 m, respectively), both exceeding their corresponding maximum allowable limits (*ΔHm* max​). The manifold diameters of 40 mm, 50 mm, and 63 mm show significantly reduced head losses of 0.940 m, 0.313 m, and 0.102 m, respectively—well within the permissible thresholds. These results confirm that manifold sizes of 40 mm and above are hydraulically suitable for the given layout.

**Figure 2. Head losses for different lateral sizes.**

**Figure 3. Head losses for different manifold sizes.**

3.3 Optimal Design Solution

To achieve the most cost-effective design of the lateral, manifold and mainline, the optimization approach was implemented. The objective was to minimize the total annual cost, which includes both the annualized fixed cost of pipes (based on per-meter cost for each available diameter) and the associated energy cost, determined from hydraulic gradients. Figure 4 shows the schematic representation of the hierarchical route-wise configuration used for annual cost optimization in a drip irrigation network. The diagram illustrates the sequential flow from emitter selection to lateral lines, manifolds, and mainline components. Each stage incorporates multiple pipe diameter options—ranging from 12 mm to 125 mm—enabling multistage optimization based on hydraulic performance and cost criteria.



**Figure 4. Hierarchical representation of route-wise annual costs and pipe size configurations for drip irrigation network optimization.**

The network structure supports evaluation of all feasible design paths from emitter to pump, facilitating the selection of an optimal combination that minimizes total system cost. This design exercise demonstrates the applicability of multistage optimization for mainline layout and sizing, confirming the robustness of the model developed.

To systematically evaluate the optimal configuration of a drip irrigation system, a route-based cost analysis was conducted by simulating all 125 possible design combinations from the emitter to the pump unit. Each route represents a unique combination of lateral, manifold, and mainline pipe sizes, with the corresponding total annual cost computed based on both fixed and energy components. This approach enabled the identification of the most cost-effective and hydraulically feasible layout for the given field conditions.

Table 3 present the total annual cost analysis for all 125 possible combinations of lateral, manifold, and mainline pipe sizes in a drip irrigation system, based on the hierarchical layout depicted in Figure 4.

**Table 4. Total annual cost (₹) of drip irrigation system configurations for various combinations of laterals, manifolds, and mainline sizes.**

|  |  |  |
| --- | --- | --- |
| **Manifold Size (mm)** | **Mainline Size (mm)** | **Total Annual Cost (₹)** |
| **Lateral line** |
| **12mm** | **16mm** | **20mm** | **25mm** | **32mm** |
| 25 mm | 63 mm | 13561 | 13534 | 13968 | 15476 | 18010 |
| 75 mm | 14190 | 14163 | 14599 | 16106 | 18640 |
| 90 mm | 15467 | 15440 | 15876 | 17383 | 19916 |
| 110 mm | 17708 | 17681 | 18115 | 19623 | 22157 |
| 125 mm | 19825 | 19798 | 20233 | 21741 | 24274 |
| 32 mm | 63 mm | 12015 | 11988 | 12422 | 13930 | 16464 |
| 75 mm | 12645 | 12618 | 13052 | 14560 | 17094 |
| 90 mm | 13922 | 13894 | 14329 | 15837 | 18371 |
| 110 mm | 16162 | 16135 | 16569 | 18077 | 20611 |
| 125 mm | 18280 | 18253 | 18687 | 20195 | 22729 |
| 40 mm | 63 mm | 11808 | 11781\* | 12215\*\* | 13723 | 16257 |
| 75 mm | 12438 | 12411 | 12845 | 14353 | 16887 |
| 90 mm | 13714 | 13687 | 14123 | 15630 | 18164 |
| 110 mm | 15955 | 15928 | 16362 | 17870 | 20404 |
| 125 mm | 18073 | 18045 | 18480 | 19988 | 22522 |
| 50 mm | 63 mm | 12054 | 12027 | 12461 | 13969 | 16503 |
| 75 mm | 12601 | 12657 | 13092 | 14599 | 17133 |
| 90 mm | 13877 | 13933 | 14369 | 15876 | 18410 |
| 110 mm | 16118 | 16174 | 16608 | 18116 | 20650 |
| 125 mm | 18235 | 18291 | 18726 | 20234 | 22768 |
| 63 mm | 63 mm | 12674 | 12647 | 13082 | 14589 | 17123 |
| 75 mm | 13305 | 13276 | 13712 | 15219 | 17753 |
| 90 mm | 14581 | 14554 | 14989 | 16497 | 19030 |
| 110 mm | 16822 | 16794 | 17229 | 18736 | 21270 |
| 125 mm | 18938 | 18911 | 19347 | 20854 | 23388 |

\*Infeasible Minimum Cost/Cost-wise optimal but hydraulically infeasible.
\*\*Optimal cost/Hydraulically Feasible Minimum Cost.

**Table 5. Hydraulic performance and cost analysis of optimal pipe sizing in a drip irrigation system.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Optimal pipe size (mm)** | **Pressure head (m)** | **Head loss, ΔH(m)** | **Discharge deviation, ΔQ (%)** | **Annual cost (₹)** | **Cost per unit area (₹/m2)** |
| **FCb** | **ECc** | **TCa** |
| **Inlet** | **End** |
| Lateral | 20 | 13.37 | 12.89 | 0.48 | 1.78 | 8270 | 3945 | 12215 | 1.82 |
| Manifold | 40 | 14.31 | 13.37 | 0.94 | 3.31 |
| Mainline | 63 | 16.26 | 14.31 | 1.95 | 6.32 |

Table 5 presents the optimal pipe size selection and corresponding hydraulic and cost performance metrics. The optimized configuration includes 20 mm laterals, 40 mm manifolds, and 63 mm mainlines. The pressure heads at the inlet and end of each section demonstrate that the system operates within acceptable pressure limits, with moderate head losses of 0.48 m, 0.94 m, and 1.95 m for lateral, manifold, and mainline segments, respectively. Discharge deviation remains within permissible limits, with 1.78% in laterals, 3.31% in manifolds, and 6.32% in the mainline—indicating satisfactory uniformity. The associated annual costs are ₹8270 (fixed cost), ₹3945 (energy cost), summing to a total annual cost of ₹12215. The resulting cost per unit area is ₹1.82/m², suggesting that the selected configuration provides a hydraulically feasible and cost-effective design solution for the given field conditions.

4. Conclusion

A multistage optimization-based optimal design approach is proposed for complete drip irrigation system. The model minimizes fixed cost, energy cost, or total annual cost for any uniform ground slope. It uses segment-wise annual costs of available pipe sizes to determine optimal pipe diameter combinations, ensuring outlet pressures remain within acceptable limits. The method ensures that the designed pipeline delivers pressures that meet the required operating conditions at all outlets. The findings reveal that hydraulic balance and economic performance, achieving the lowest total annual cost ₹12,215 and ₹1.82/m². Overall, this study contributes a computationally efficient and hydraulically robust framework for optimizing drip irrigation systems. The proposed method supports design engineers and practitioners in selecting layout configurations and pipe sizes that minimize costs while ensuring uniform water delivery, thereby promoting sustainable water resource management in agriculture.

Consent (where ever applicable)

I have my consent for this material to be published in the journal and associated publications without limit on the duration of publication. I understand that the material will be published in the journal will be included in any reprints of the published article. I understand that my name will not be included in the published article, and that every effort will be made to keep my identity anonymous in the text and in any images. However, I understand that complete anonymity and control of all uses cannot be guaranteed.

Ethical approval (where ever applicable)

Not Applicable

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