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Nidhi Nagabhatla · Yusuf Mehta ·
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Recent Developments in Water Resources and Transportation Engineering

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Comprehensive Assessment of Simulation Tools for Analyzing Seepage Through Earthen Dams

Shravani Yadav, Shruti Jain, and Brijesh Kumar Yadav

Abstract Seepage is one of the primary reasons for the failure of earthen/embankment dams worldwide. As approximately 40% of earthen dams fail due to excessive and uncontrolled seepage, it is crucial to manage seepage in order to improve their stability and life. Numerical experiments are favored for predicting seepage flux under changing climatic conditions for earthen dams made of varying geological materials. In the present study, the application of numerical tools to analyze seepage through earthen dams is critically reviewed for popular software's such as SEEP/W, ANSYS, HYDRUS, PLAXIS, MODFLOW, SVFLUX, and FEFLOW. An overview of governing equations and limitations of these models is briefly explained along with their relative advantages. A comparative analysis is then carried out for a characteristic earthen dam using the simulation results of SEEP/W and FEFLOW. It has been found that the results obtained from FEFLOW are slightly accurate, and therefore, a detailed seepage study is finally being conducted for the Ambawali Dam, Haryana, India using FEFLOW. The results of this study can be used by field engineers in selecting the appropriate model(s) based on dam body and their surrounding conditions to manage the seepage flux effectively.

Keywords Earthen dams · Seepage analysis · Numerical modeling · Dams safety

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1 Introduction

Earthen dams are the most prevalent form of dam, which are used to store water for irrigation, hydropower, municipal water supply, and to control floods and are built with naturally accessible materials. An earthen dam that has been appropriately constructed and designed will be stable against seepage and evaporation losses [7, 9, 19]. Although losses from evaporation cannot be controlled, and seepage losses can be reduced with proper construction methods. Seepage is the flow of water through the pores or fractures in the dam body and is one of the most important aspects of dam analysis and design. Thus, it is important to understand the seepage characteristics of dams to make sure the stability and performance of the dam.

The rate and direction of water flow through an embankment are determined by a seepage analysis. Controlling seepage through the embankment dam as well as its foundation is an essential factor for determining its safety. Typically, seepage occurs between a dam's upstream to downstream faces and phreatic surface describes the upper portion of this stream's percolating water. The seepage issue is the most frequently observed in earthen dams, and it has a direct effect on the stability of embankments, the sloughing of slopes as a result of increased pore water pressure, and internal erosion that may ultimately result in piping. According to literature, seepage failures such as piping and sloughing have caused approximately 40% of earthen dams to collapse [2]. Therefore, preventing seepage through dams is the key to creating safe dams that serve their intended purpose of storing water.

A significant aspect in the planning and building of dams is the detection of seepage through the foundations and embankment. For field engineers and researchers, the estimation and study of seepage flow behavior pose significant challenges. Researchers have used empirical, visual, and recently numerical approaches to quantify the water seepage under various boundary conditions [9]. Numerical models can help researchers to investigate seepage through earth-fill dams under varying hydrological and geological conditions at various sites.

For instance, physical models have been used in several studies to provide a basic overview of seepage behavior as well as rate of flow through dam body and top seepage line [7, 10, 14]. Numerical models are gaining popularity to overcome the limitations of physical modeling and to consider the complexity of the real-field situations. Thus, the main objective of this study is to provide a thorough overview of the various numerical tools available for earthen dam seepage analysis along with a case study using FEFLOW.

2 Methods of Analyzing Seepage

Seepage losses can be analyzed analytically, graphically and numerically for steady-state and transient flow conditions. Seepage flow can be obtained from the Darcy's law $Q = kiA$. The actual seepage for multi-dimensional flow can be analyzed using the Laplace Equation $\nabla^2 = 0$, the solution of this equation is quite complex and various considerations are made to solve this equation analytically. The solution of Laplace equation can also be represented graphically known as Flow Net, which is a set of equipotential lines and flow lines. The flow net can be used to calculate the seepage flow as $q = kH(N_F/N_D)$ or isotropic soils. While for non-isotropic, $q = \sqrt{K_H \cdot K_V} H \cdot N_F/N_D$ soil medium, dam section is drawn at same vertical scale but to a transformed horizontal scale (K_V/K_H).

Seepage through a heterogeneous, anisotropic, saturated–unsaturated soil can be given by governing a partial differential equation, which is derived by taking a representative elemental volume and conservation of mass [17]. The partial differential equation for transient process with the assumption that total stress remains constant that is given by Eq. (1).

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) = \frac{S}{T}\frac{\partial h}{\partial t} \tag{1}$$

where k_x, k_y and k_z are the coefficients of permeability of soil in x, y and z direction, respectively, S is storativity and T is transitivity.

Causes of Uncontrolled Seepage

The problem of seepage occurs due to poor compaction of soil in foundation, embankment of dam and of its surrounding site. Poor foundation with rodent holes, tree roots, cracks, joints in earth rock, improper design of filter and drainage, shrinkage and settlement in soil media, excessive uplift pressure are the other reasons of seepage initiation. Due to these, dam failures by pipping through the body and foundation of the dam, generation of excess uplift pressure, erosion of embankment materials, and solubility of weak soluble rocks occur [12, 16, 18]. These failures will eventually lead to failure of the entire dam structure and cause catastrophic loss in terms of life and property.

3 Models for Seepage Analysis

Various numerical techniques of efficient computational period and enhanced visualization have emerged over the past decades for solving flow through complex porous media. Analytical solutions to seepage problems are also developed for seepage quantification. However, these solutions are based on assumptions of linear flow and are therefore only applicable to dams with simple geometries. The finite element method (FEM) is a numerical technique for solving partial differential equations (PDEs) by discretizing them into a set of finite elements. This method is used to analyze seepage problems in earthen dams by dividing the dam into small triangular or rectangular elements and solving the governing equations at each element. The finite difference method (FDM) is another numerical technique for solving PDEs by dividing the domain into a set of smaller cells and approximating the derivatives of the PDE at each cell. This method is used to analyze seepage problems in earthen dams by dividing the dam into small grids and solving the governing equations at each grid point. The most widely used numerical tools suitable for simulating seepage are described below.

FEFLOW is an acronym of Finite Element subsurface FLOW and transport system introduced in 1979. It is effective and interactive groundwater modeling system for variably saturated 3D and 2D transient or steady type flow. It can be effectively used for describing the spatial and temporal distribution and reactions of groundwater contaminants to model. FEFLOW is a powerful and comprehensive tool to model complex subsurface processes, yet it is easy to use. FEFLOW works with discrete feature approach, which provides the crucial link between the complex geometries for subsurface and surface continuum in modeling flow, containment mass and heat transport process. In the FEM context, the 3D mesh for the porous matrix can be enriched by both bar (channels, mine slopes) and areal (overland, fault) elements. FEFLOW provides 1D and 2D discrete feature elements, which can be mixed with the porous matrix elements in two and three elements. The basic balance equations used in FEFLOW are fluid mass conservation, fluid momentum conservation, contaminant mass conservation, and energy conservation. First step for creating a FEFLOW model is create soil geometry to a scale accounting maps and model boundaries, supermesh, finite element mesh and expansion of model to three dimensions. Secondly, inputs for model parameters are provided like, geometry, process variable, boundary conditions, material properties, auxiliary data, user data and discrete features. One of the limitations of this software is it is expensive and complex to learn. A case study illustrating the application of this software is mentioned in Sect. 4.

Geo-Studio-SEEP/W is a user-friendly software that is free for students, allowing them to conduct a variety of analyses linked to geotechnical investigations. For the analysis of seepage through earthen dams, SEEP/w program is used, which is a sub-program of Geo-studios software [14]. It is based on Darcy's Law, which describes movement of water through both saturated and unsaturated soils. Seepage analysis can be performed using SEEP/W. The likelihood of the dam failure because of seepage has been investigated analytically using the Geo-studio program. The limitation of SEEP/W is its restrictions related to the hardware's existing capabilities. SEEP/W is exclusively designed for flows that adhere to Darcy's Law adjacent to the ground surface. However, soil moisture may vaporize close to the surface and SEEP/W formulation does not include this element in its simulation [6].

MODFLOW is a 3-D groundwater flow model, which is developed by United States Geological Survey and works based on finite difference method. In the finite difference technique, terms that are derived from the variations in head values at different cells are used to replace the partial derivatives to represent study domain in a finite number of distinct points [11]. The model generates a set of simultaneous algebraic equations, whose solution provides the head values at particular times. These numbers represent an approximate representation of the time-varying head distribution, which would result from the groundwater flow equation of the partial differential nature. The MODFLOW models aquifer systems with saturated flow conditions by assuming constant groundwater density. The user has to enter aquifer attributes for each cell in the area of the aquifer system. In order to implement the solution, time steps are taken at each aquifer cell of the study domain [1]. The overall aquifer water budget is also simulated by MODFLOW in addition to the water levels. One of the limitations is that it does not take into consideration the capillary-induced infiltration that occurs at the beginning of wetting, when negative pressure difference might be substantial in comparison to gravity potential gradients. For considering density impacts, additional modules are integrated with MODFLOW model.

For the evaluation of the time-dependent, anisotropic and non-linear performance of soils and rocks, geotechnical solutions require sophisticated modeling techniques. In order to analyze deformation, stability, and groundwater flow in multi-dimensions, ***PLAXIS*** was developed based on geotechnical finite element method. The nonlinear behavior of soil and rock formations can be accurately modeled using PLAXIS software [5]. The findings of various studies reveal that the effectiveness of this software is capable of simulating behavior of embankment dams. One of the limitations of PLAXIS is that it is not able to define arbitrary geometries of the study area.

Likewise, ***ANSYS*** is a general-purpose finite-element modeling tool, which is used to numerically solve a wide range of mechanical issues. Similar to other finite element applications, ANSYS is organized into three major processors: pre-processor, solution processor, and postprocessor. The assessment of seepage using the Ansys software is performed using thermal methods [10]. To calculate the factor of safety, various methods such as Limit balance and Bishop methods are utilized. It has been noted that the rate of seepage obtained using ANSYS software usually underestimates in comparison with GEO-STUDIO.

A computer program called ***HYDRUS*** enables the modeling of water, mass, and heat movement in 3-D mediums with varying saturation levels. The finite element approach is used to calculate flow through soils with a mixed flow regime [15]. The model formation begins by defining the study area followed by discretization mesh developed. Seepage face boundary condition is employed along the air-side embankment. The software iteratively calculates the length of the seepage face using Picard's method. It uses Richard's equation to simulate flow through variably saturated medium. The quantitative assessment of water flow through the unsaturated soil zone is performed to estimate using the appropriate parameters of various soil types. One of the HYDRUS software's limitations is that it presumes the pressure head will always be steady and equivalent to zero along the seepage face.

PDEase2D is very adaptable and simple to use program that addresses issues in a variety of domains, including heat transfer, fluid and solid mechanics, electromagnetic, groundwater movement, and quantum physics. The time required to deal with nonlinear static and dynamic problems up to 32 constraints is quite less by its concise input language, automatic grid generation, and refining. Through PLAXIS 3D, the stability of dams and seepage is analyzed, and the results were appropriate [4].

SVFLUX software is employed to perform seepage analysis on both two- and three-dimensional domains. It can be employed in conjunction with the database tool 'Soil Vision' to do analysis without requiring a comprehensive laboratory process. The governing equation for seepage is obtained by solving the conservation of mass for a typical elemental volume. SVFlux solves a problem by enabling the input of complex geometry using survey information. In order to model water flow, reasonable boundary constraints are applied to the model, and flux sections are placed all throughout the area. Solution of non-linear equations converge well using this tool and it supports a wide range of formats for the input of material parameters including unsaturated soils.

This section provides a summary of the most widely used software programs for analyzing seepage through earthen dams. Additionally, a case study illustrating the use of these software's has been presented in Sect. 4.

Since most of the dam bodies are partially saturated/unsaturated, FEFLOW and SEEP/W seem capable of simulating these conditions effectively. Moreover, a significant variation in the water level in the dams during changing influx and outflux conditions can change the fraction of saturated/unsaturated portions of the dam's body. Initially, a characteristic dam site is used to compare the results of these two models followed by taking a real-field dam site.

4 Seepage Flow Through Earth Dams Using FEFLOW and SEEP/W

Seepage through earthen dams can be analyzed using above-mentioned tools and based on the limitations of some models, FEFLOW and SEEP/W are used for a comparative study as also suggested by Arshad et al. [3], Molla [13]. A case of homogeneous earth dam of 15 m height is taken and steady state is taken here for a constant hydraulic head of 12 m, and the results are shown in Fig. 1.

Figure 1 represents the variation of hydraulic head over the dam cross-section, the selected FEFLOW and SEEP/W models. The dashed line represents the phreatic

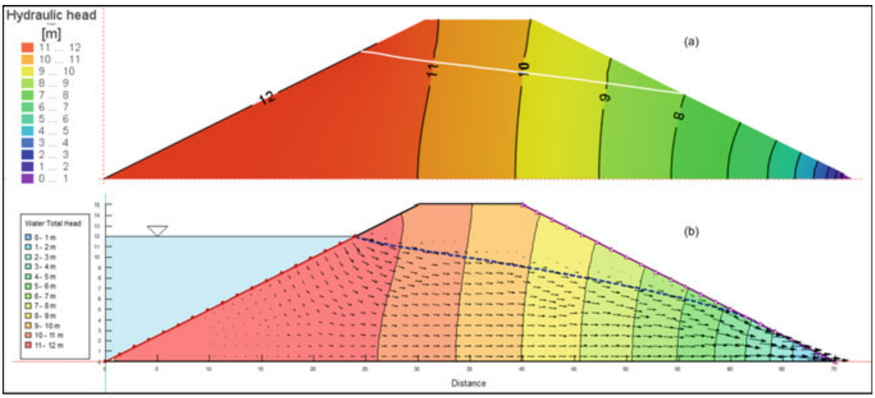

Fig. 1 Comparative study of seepage through earth dams using **a** FEFLOW, **b** SEEP/W for a homogeneous earth dam

line, i.e., zero pressure line (Fig. 1b), which may vary for case to case. After amassing the mass balance of this case study, it is found that FEFLOW predicts seepage more accurately than the SEEP/W model [8]. Thus, FEFLOW is used further to predict the rate of seepage flow and phreatic line for real field dam conditions.

For the seepage analysis, Ambawali Dam, Haryana is considered which is a zoned Earthen dam. FEFLOW is a numerical model that uses Darcy's equation for saturated zone and Richard's equation for the unsaturated zone. The Ambawali Dam is situated on Somb-Pathrala Nadi of Yamuna River Basin, having height of 23.25 m above the deepest bed (344 m), top width of 6 m, and length of dam is 550 m, as shown in Fig. 2. Seepage in the Earth dam occurs through dam body and foundation of the dam but for this study, the impervious layer in foundation is assumed at the 50 m from the deepest sea bed and a 2D flow model is constructed in FEFLOW. Further a steady-state stimulation is taken to obtain the seepage flow rate and phreatic line.

The finite element mesh is generated with a total of 44,458 elements of triangular type. The hydraulic boundary condition of the upstream side is given as FRL (363 m), i.e., hydraulic head of 19 m and downstream of the dam is seepage face side. For the seepage analysis, there are two main parameters, i.e., hydraulic conductivity and unsaturated flow porosity. Since Ambawali Dam is a zoned Earth dam, the parameters of different zones are taken according to the type of materials in the particular zone. The used parameters for this model run are listed in Table 1.

Parameters for solving an unsaturated model include empirical model parameters like saturation limits and Modified Van Genuchten Constants. In saturation limits, there are two parameters, i.e., maximum saturation and residual saturation. Considering the general values of maximum saturation as unity and residual saturation as 0.0025. Modified Van Genuchten model gives a relation for effective saturation and relative conductivity in terms of residual and maximum saturation levels. The value of constant parameters of the Modified Van Genuchten Model, i.e., α, n, m, and δ are listed in Table 1 and assigned in the model inputs based on the dam composition.

Steady-state stimulation is performed to find hydraulic head, pressure line, and rate of seepage flow. The imbalance in mass budget is 0.00030046 m^3/d, which is very small and its numerical model is quite accurate and can be used for further analysis.

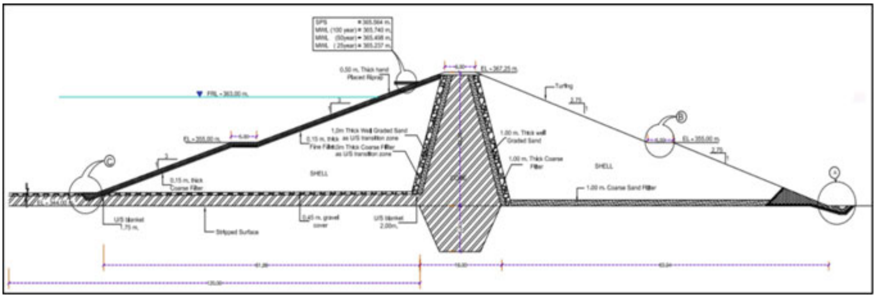

Fig. 2 Cross-sectional geometry of Ambawali Dam of Haryana (*Source* Completion Report of Ambawali Dam of Haryana)

Table 1 Hydraulic conductivity and unsaturated flow porosity of different zones

Serial number	Zone	Hydraulic conductivity (m/s)	Unsaturated flow porosity
1	Core of the dam	1.28×10^{-6}	0.374
2	Sand filter	9.23×10^{-5}	0.311
3	Coarse filter	6.6×10^{-3}	0.416
4	Shell (dam body)	2.21×10^{-5}	0.29
5	Foundation soil	5.23×10^{-6}	0.332

The seepage rate is computed as 4.16 m^3/d for the selected conditions Steady-state stimulation is performed for the hydraulic head of the upstream side as free reservoir level. The drops in hydraulic head and pressure distribution are shown in Figs. 3 and 4, respectively. The phreatic line that drastically lowered down at the core of the dam due to the presence of the clay formation is illustrated in these figures clearly. However, the phreatic line across the dam body is found not attenuated so sharply in left and right sides of the dam core. It is to be noted that the head loss in center of the body is more prominent as compared with the rest of the dam body as depicted by the interval of the isolines.

Thus, it can be concluded that the numerical model runs of the dam with FEFLOW are found quite accurate and are recommended to predict the rate of seepage flow and phreatic line under steady-state conditions for a dam made of different geological materials. It is observed that the composition of the earth dam body plays an important role in controlling piping and internal erosion. Further, it is found that the core body size of the earthen dam plays a crucial role in controlling the phreatic line and the head loss. Apart from this, proper seepage monitoring and instrumentation during and after the construction of the dam are recommended for identifying and controlling the dam seepage.

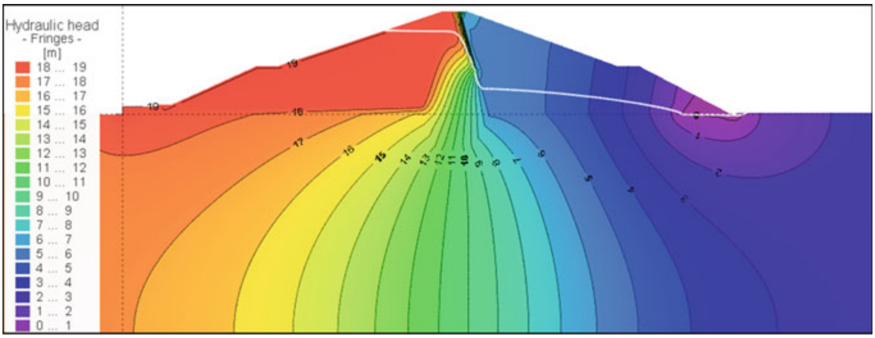

Fig. 3 Variation of hydraulic head over the cross-section of the dam

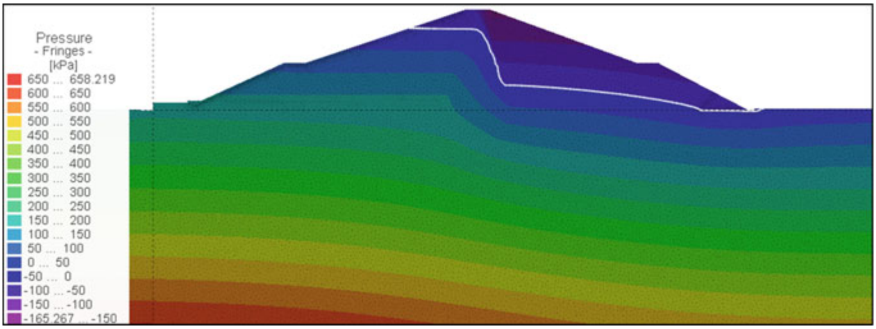

Fig. 4 Phreatic line (white) and variation of pressure over the cross-section of the dam

5 Conclusion

Numerical techniques are found powerful tools for simulating seepage in complex dam's bodies. Seepage analysis models employ numerical modeling techniques of finite element and the finite difference methods. Software such as SEEP/W, ANSYS, HYDRUS, PLAXIS, MODFLOW, and SVFLUX are employed by various designers and researchers for simulating various elements of seepage in earthen dams. Effectiveness of drains, internal soil stress, dam stability, settlement, prediction of seepage, and calculation of total seepage flow rate are some of the parameters that can be modeled using these numerical tools with some pros and cons. A comparative analysis for a homogenous earthen dam shows that FEFLOW conserves the mass more accurately than SEEP. The Ambawali Dam, Haryana that is a zoned earthen dam is used to show the capabilities of FEFLOW for seepage analysis and is recommended to use for analyzing seepage flow through earthen dams made of varying geological materials.

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Nature-Based Solutions as a Pragmatic Approach Towards Flood Resilient Cities

Madhuri Kumari, Pranjal Pandey, Akanksha, and R. K. Tomar

Abstract Flooding is one of the most common and severe disasters that afflicts several Indian states every year, and it is frequently followed by the spread of epidemics. The cities along the banks of river or seashore face great pressure in dealing with flood disaster management and such experience will mount up in the coming decades due to the rising intensity and frequency of natural hazards triggered by climate change. Therefore, there is a need to develop an environment-friendly pragmatic approach for making such vulnerable cities into a flood resilient city. In recent decades, flood risk reduction and management strategies are seen to be supplementing the traditional technical and engineering methods with nature-based solutions (NBS). NBS brings in multiple benefits to people and the social system by contributing towards improvement in quality of life, strengthening, and promoting ecological balance. This paper presents a conceptual framework for the integration of NBS into current Flood Risk Mitigation and Management (FRM) strategies. This framework is intended as a tool to be adopted by decision-makers to operationalize the NBS integrated pragmatic approach and work towards developing flood-resilient cities.

Keywords Flood resilience · Nature based solutions · Flood risk mitigation · Disaster risk reduction · Urban flooding · NBS framework

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1 Introduction

India experiences a variety of natural disasters and hazards, with flooding being the most significant. Flooding is defined as excessive surface runoff that inundates towns and farmland [1]. It is the most common natural catastrophe. The Intergovernmental Panel on Climate Change (IPCC) predicts that the region impacted by monsoon seasons will increase globally with rising precipitation levels, resulting in more flood events [2]. Flooding affects 14.6% of India's land area [3]. From 1978 to 2006, India had 2443 flood incidents causing 16 billion USD in damages [4]. During the monsoon season, which brings low to heavy rainfall, residents of Indian cities often experience flooded streets and waterlogged homes [5]. Monsoon season in India sees 80% of precipitation occur in a short time from June to September, leading to the highest number of flooding incidents (urban, rural, and coastal) in various regions of the country [6, 7]. Experts have long discussed the connection between climate-related disasters and their aftermath (socioeconomic losses and public health) [8]. Natural disasters such as flooding also pose a significant public health risk from water and air-borne infectious diseases, which have become increasingly prevalent over time [9]. Figure 1 shows that the states of Maharashtra, Tripura, West Bengal, and Bihar have had the highest number of flooding incidents in the last 15 years.

Flooding is classified into three types (ref. Table 1): rainfall-induced (pluvial), river flooding (fluvial), and tidal flooding (coastal) [10]. The preponderance of flood incidents during the monsoon season is triggered by prolonged rainfall and heavy downpours [11]. All river basins in India experience flood events; however, the Ganga and Brahmaputra River basins have the highest number and severity of flood events [12]. The Ganga River zone, the Brahmaputra River zone, the North-West River zone, and the Deccan (coastal) zone are the four principal flood zones in India [13].

Urban floods are common and have become serious issues around the world even in India as well [14]. Flooding happens most frequently in metropolitan areas due to substantial monsoon precipitation in a short period of time, causing significant damage to life and property. In India, 1561 urban local bodies out of 7935 are flood-prone [5, 15]. Figure 1 depicts the number of times flood occurred (flooding frequency) state-wise in India over the span of 15 years.

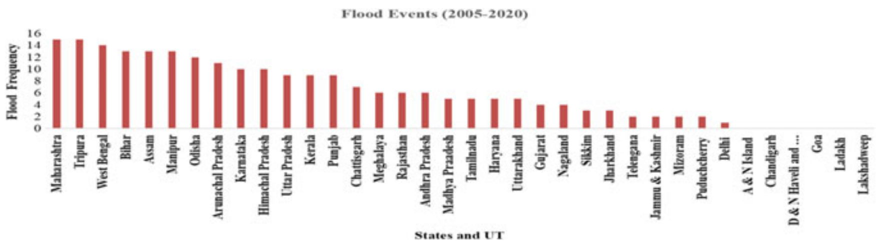

Fig. 1 Flood frequency in the last 15 years. (*Source* Annual disaster reports (2005–2020), Indian meteorological department (IMD))

Table 1 Types of floods in India

Type of flooding	Descriptions
Rainfall induced flooding	Heavy amount of rain over minutes to hours inundates creeks and dry valleys
River flooding	The floodplain is inundated when water from a river or drainage channel cannot be contained within its stream channel or by built structure. It occurs often seasonally. This is the most common flooding
Tidal flooding	Increasing sea level caused by storm surges generated by tropical cyclones and tsunami

The increasing urbanization in India has resulted in Indian cities being constructed hastily and in a haphazard manner, which has contributed significantly to the increased risk of an urban flood [16]. 30–40% more rainfall is observed in Indian urban cities than in rural areas [15]. Figure 2 shows the major flood prone regions in India. Metropolitan cities such as Mumbai, Delhi, Bangalore, Assam, Chennai, and many others are key examples of cities that face frequent urban flooding events, demonstrating the current state of flood management in Indian cities. Most of these cities are unplanned, have poor drainage systems [17]. Because of high population density and inadequate infrastructure, the socioeconomic losses and public health risk due to flooding aftermath are significantly greater in urban regions than in rural ones, resulting in the rapid growth of flood occurrences in metropolitan areas [18].

Significant socioeconomic and environmental consequence are the results of flooding, including the loss of living beings' lives, infrastructure destruction, and damage to the natural environment [20]. There are examples of recent flood events: Jammu and Kashmir flooded in 2014 because of constant rain. Even after the Indian army evacuated 11,000 people, 138 people died. River Jhelum and its tributaries flew above the danger mark. Due to this, the Vaishno Devi Yatra has been suspended [21]. Chennai had suffered 3 billion losses and live losses of 138 people in the 2015 flood. In 2018, Kerala faced massive flooding due to unusual rainfall and the sudden discharge of water from reservoirs [22]. Assam Flood 2020 refers to a major flood event of the Brahmaputra River. 5 million people were affected with the loss of 123 people [23].

In Indian cities, measures have been taken to prevent floods. Due to the diverse weather patterns across different regions in India, flood mitigation measures are tailored to each location based on its climate and rainfall pattern. These locations can range from areas near dams to hilly, marshy, and coastal regions. The measures are mainly divided into structural and non-structural categories. Non-structural measures include using automatic weather stations to gather real-time information on rainfall and flood warnings [24] and conducting flood vulnerability mapping to identify high-risk areas. Structural measures include enhancing the urban drainage system with sustainable solutions like detention ponds or storage channels to make cities more resilient to floods [25].

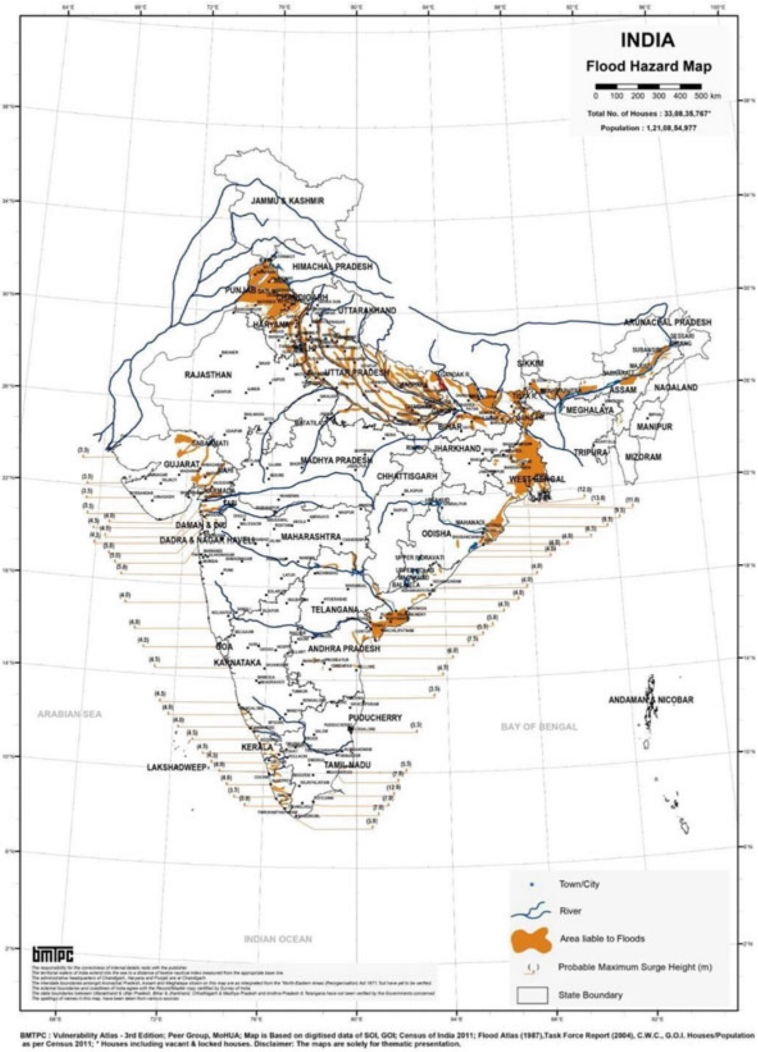

Fig. 2 Flood prone regions in India [19]

In addition to conventional strategies, nature-based solutions (NBS) are also being used for flood risk mitigation and prevention. NBS are strategies that address environmental challenges such as resource depletion, disaster risk reduction, and ecosystem degradation caused by urbanization and climate change [26]. This study focuses on the benefits of using NBS for socio-economic and public health purposes and proposes a framework for identifying and implementing nature-based projects in Indian cities to enhance flood resilience.

2 Nature-Based Solution for Flood Resilience Cities in India

According to the International Union for Conservation of Nature (IUCN), Nature-Based Solutions (NBS) are approaches to sustain, restore, and control natural or modified ecosystems in a sustainable manner, resulting in not only the elimination of environmental and social barriers but also the improvement of the physical and mental well-being of all living species through positive environmental externalities such as increased biodiversity [27]. The IUCN outlines eight principles that NBS activity should follow: embracing nature conservation, being integrated with other societal challenges, being determined by site-specific natural and cultural contexts, producing societal benefits fairly and equitably with transparency and broad participation, maintaining biological and cultural diversity and the ability of ecosystems to evolve over time, being applied at the landscape scale, recognizing trade-offs between immediate economic benefits and future ecosystem services, and being an integral part of overall design policies [28].

Traditional engineering solutions or structural ways of mitigating flood vulnerability have been used for centuries, such as building embankments, dams, levees, and canals [29]. These “hard” or “grey” infrastructure solutions have proven to be uneconomical and damaging to habitats and ecosystems, causing the loss of settlements, and forcing people to relocate without input or choice [30]. To address these drawbacks, there has been a growing interest in examining the role of nature-based projects as an alternative to traditional hard engineering solutions for flood risk mitigation in cities [31]. Concepts like “Nature-based solutions,” “ecosystem-based adaptation,” “eco-DRR,” and “green infrastructure” have emerged as potential alternatives to traditional grey techniques, using natural processes and ecosystem services for purposes such as flood risk reduction and improved water quality [32].

In terms of flood management, NBS are divided into two categories: Natural Water Retention measures (NWRM) and Natural Flood Management (NFM) [33]. NWRM involves retaining water in and on plants, increasing plant transpiration, improving soil health, creating ponds and wetlands, and reconnecting floodplains. NFM uses landscape features to control flood risk by minimizing the maximum flow discharge and leveling it out [34]. These methods have the potential to remedy ecological hazards more effectively and NWRM can be used in various aspects of water management, such as water quality [31]. Floodplain restoration can also be considered an NBS that reduces the likelihood of flood-related disasters and can provide benefits for both ecosystem restoration and flood damage prevention [35, 36].

2.1 Ecosystem-Based Adaptation for Flood Impact Mitigation

Ecosystem-based adaptation initiatives generally focus on long-term adaptation to chronic and irreversible stressors, such as gradually warming temperatures, sea level rise, and glacial melting. Employing a range of biodiversity and ecosystem conservation approaches, such initiatives help people adapt to the adverse effects of climate change and mitigate climate-related hazards.

Ecosystem-based disaster risk reduction aims to reduce hazard events and/or communities' exposure and vulnerability to them. Disaster risk reduction is typically focused on near-future risk, such as landslides or floods. Such initiatives may involve, for example, the installation of early warning systems. But we can also reduce disaster risk through the planting of trees to stabilize slopes. Ecosystem-based disaster risk reduction addresses both non-climate-related events, such as earthquakes and tsunamis and climate-related events like hurricanes and heat waves, as well as other kinds of hazards. While different, these approaches share an emphasis on ecosystem management, restoration, and conservation and can be thought of as interventions that are implemented on a hazard continuum that ranges from near-term, often sudden events such as landslides, to longer term, generally gradual events such as sea level rise.

At the project or operational level, they are often indistinguishable. Environmental management is central to both approaches and can be combined with measures that explicitly reduce disasters and climate impacts. Such interventions have been around for decades, but it's only recently that we have started to emphasize disaster risk reduction and climate change adaptation.

3 Proposed Framework for Integrating NBS in Flood Resilience

Eco-engineering can have an impact on the structural components that support the ecosystem's functioning [37]. One notable example is the Azamenose Riverine Wetland Restoration Project in Saga, Japan, led by the Ministry of Land, Infrastructure, Transport, and Tourism in partnership with various stakeholders including local communities, NGOs, local governments, and academics, particularly Kyushu University [38]. In this project, a wing-shaped flood control basin was built along the curved part of the Matsura River to absorb overflow downstream [39].

These flood control basins not only reduce the risk of flooding but also provide habitats for biodiversity, as seen in wetland creation, which is a common approach in urban areas for flood control, improved drainage, and ecosystem restoration [40]. Wetlands, like those developed as part of an eco-neighborhood initiative in Geneva, Switzerland, serve to collect excess rainwater and provide a habitat for birds [41]. Ecological engineering plays a crucial role in incorporating modern technology, such as early warning systems for landslide movements and river height monitoring, or climate-smart agriculture, into these established and successful methods for promoting community resilience [42]. The concept of "building with nature" is often used to describe this process, but it should be used cautiously as many procedures, like using deep-rooted grasses to stabilize slopes, may be more accurately described as "weaving or knitting with nature" [43].

Ecological engineering is often described as "building with nature and people" due to its emphasis on involving local communities in its implementation [44]. It involves impacting the living tissue of ecosystems and the organisms that make them up, as well as the underlying structures such as mountains and valleys [45]. Efforts are underway to further the implementation of Nature-Based Solutions (NBS) for flood risk reduction through publications such as the World Bank's Implementing Nature-based Flood Protection (2017) and WWF's Guidelines on Natural and Nature-Based Flood Management: A Green Guide (2017).

The study suggests a framework for integrating NBS into current Flood Risk Mitigation and Management (FRM) methods in Indian urban cities. The framework begins by identifying flood hazards, categorizing them into three types: extreme weather events, riverine flooding, and tidal flooding. The next step involves determining the types of flood risk mitigation solutions, which are divided into non-structural and structural. Non-structural solutions involve policy development, public awareness, early-stage flood warning, and monitoring. Structural solutions include hard engineering solutions, soft solutions (i.e., nature-based solutions), and hybrid solutions combining both hard and soft approaches. To effectively reduce flood risk, it is recommended first to apply non-structural solutions and then consider structural solutions by prioritizing NBS whenever possible as part of an integrated approach. In the case of no other options, then gray solutions can be selected. With NBS in focus, the framework further focuses on the guiding principles describing key considerations [46] that are taken into consideration when planning Nature-based projects for flood risk mitigation. These majorly five principles to guide nature-based flood development in cities are as follows:

1. **System scale perspective**: Figure 3 depicts a system-wide review on the basis of spatial extent, time scale, local socio-economic, environmental, and institutional factors should be the first step in addressing nature-based solutions for climate change adaptation and disaster risk reduction.
2. **Risk and benefit assessment of a full range of solutions**: A complete assessment of the risks and benefits of the whole spectrum of possible measures, including risk reduction benefits as well as social and environmental consequences should be carried out.

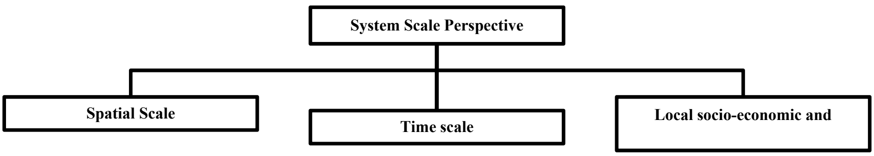

Fig. 3 Types of system scale perspective [47]

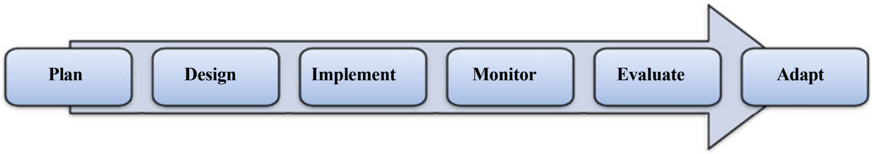

Fig. 4 Adaptive management process (CEDA, 2015)

3. **Standardized performance evaluation**: Nature-based solutions for flood risk management need to be tested, designed, and evaluated using quantitative criteria.
4. **Integration with ecosystem conservation and restoration**: Nature-based solutions for flood risk management should make use of existing ecosystems, native species, and comply with basic principles of ecological restoration and conservation.
5. **Adaptive management**: Nature-based solutions for flood risk management need adaptive management based on long-term monitoring. Figure 4 shows the process flow of adaptive management process, which contributes to ensuring NBS's sustainable performance.

The adaptive management cycle is based on an objective or outcome that may be predicted. Implementation, monitoring, data evaluation, decision-making, and adjustment of possible management measures are all parts of this process. This cycle should be performed at regular intervals throughout the measure's lifespan. The adaptive management cycle not only ensures constant management after the project is completed but also serves as a foundation for developing lessons learned for future projects. In addition to the principles, the World Bank (2017) [33] report outlines the processes for implementing a potential nature-based flood resilience project in the city. These eight implementation processes combine to form the framework's final step, resulting in a full and effective nature-based flood management project in both non-coastal and coastal communities. Figure 5 provides a summarised view of the proposed framework for integrating NBS as flood risk management tools in cities. The eight steps to successfully implementing any nature-based initiative are as follows (Fig. 6).

4 Discussion and Conclusion

Nature presents various answers to the multiple challenges humanity faces today, and there is still time to put these into practice. As the global climate crisis intensifies, natural disasters are becoming more frequent. These are partly due to climate change and partly due to poor land and resource management. The implementation of nature-based solutions for climate and disaster resilience is already taking place worldwide, and many have the potential to have a global impact. These solutions are sustainable, cost-effective, and bring multiple benefits. They can be used to tackle a variety of

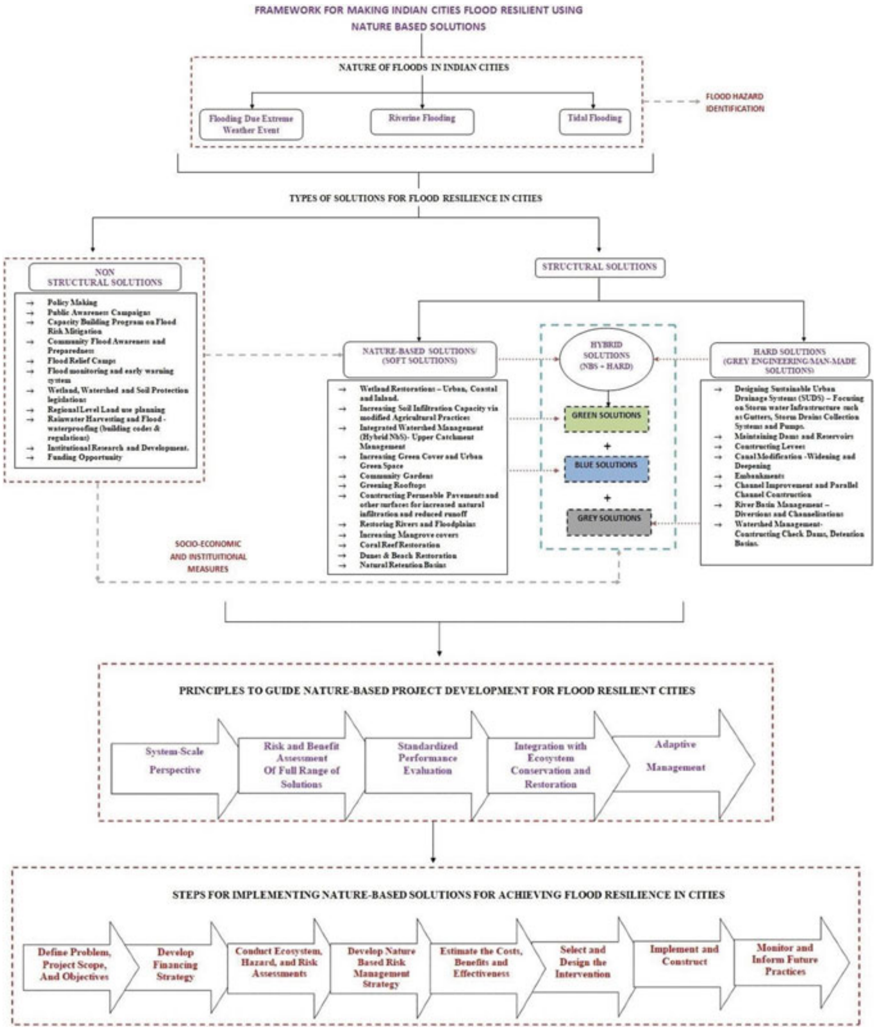

Fig. 5 Proposed framework for integrating NBS as flood risk management tools in cities

issues, from reducing carbon emissions to solving societal problems such as income inequality, food security, and other inequalities.

One main goal of nature-based solutions is to address problems caused by natural hazards such as earthquakes, floods, and landslides. People's decisions often contribute to hazards becoming disasters. For example, building in a floodplain increases a town's risk of flooding. Efforts such as planting trees on steep slopes to prevent landslides or relying on traditional flood management techniques such as water harvesting and conservation ponds can be made to reduce urban flooding [48].