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Performance evaluation and modelling studies of gravel–coir fibre–sand multimedia stormwater filter

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A horizontal flow multimedia stormwater filter was developed and tested for hydraulic efficiency and pollutant removal efficiency. Gravel, coconut (*Cocos nucifera*) fibre and sand were selected as the media and filled in 1:1:1 proportion. A fabric screen made up of woven sisal hemp was used to separate the media. The adsorption behaviour of coir fibre was determined in a series of column and batch studies and the corresponding isotherms were developed. The hydraulic efficiency of the filter showed a diminishing trend as the sediment level in inflow increased. The filter exhibited 100% sediment removal at lower sediment concentrations in inflow water ($>6\,g\,L^{-1}$). The filter could remove NO_3^-, SO_4^{2-} and total solids (TS) effectively. Removal percentages of Mg^{2+} and Na^+ were also found to be good. Similar results were obtained from a field evaluation study. Studies were also conducted to determine the pattern of silt and sediment deposition inside the filter body. The effects of residence time and rate of flow on removal percentages of NO_3^- and TS were also investigated out. In addition, a multiple regression equation that mathematically represents the filtration process was developed. Based on estimated annual costs and returns, all financial viability criteria (internal rate of return, net present value and benefit–cost ratio) were found favourable and affordable to farmers for investment in the developed filtration system. The model MUSIC was calibrated and validated for field conditions with respect to the developed stormwater filter.

Keywords: stormwater filter; fibre media; fabric screens; water quality parameters; hydraulic efficiency; pollutant removal; economic analysis; model validation

1. Introduction

Water has always asserted its position as the global elixir of life as needed not only by mankind but also by all flora and fauna alike. Even as the global population has been exploding in an exponential progression, over-exploitation and unscrupulous pumping have resulted in a precarious situation of water becoming the 'liquid gold' that is to be 'mined'. Water resources development remains the primary key to open up the vistas of sustainability of agriculture and the standard of living by way of industrialization or urbanization. Technological advancements and industrial growth warrant an addendum of existing water resources that are primarily exploited by the agricultural sector.

Surface rainwater harvesting essentially concerns the interception and storage of surface runoff on a watershed basis. The quality of surface runoff collected will always reflect the degree of contamination acquired along the flow path of runoff. It is observed that many rainwater harvesting structures, both big and small, for drinking as well as irrigation purposes, were either abandoned or underutilized because of problems related to stored/output water quality.

Barron [1] stated that with adequate operation and maintenance of the collection areas, filter and tank systems, good quality water could be obtained by collecting rainwater from rooftops or direct surface runoff. However, it is observed that very few hydraulically efficient and cost-effective filtration mechanisms have been developed so far which can effectively be used for cleaning the inlet water to the harvesting tanks. The current trend is to use chemicals or high cost materials such as perlite, nano-carbon etc. as filter media and a very few studies have so far been reported about the use of environmental friendly, biodegradable, low-cost materials such as natural fibres as filter media.

The runoff from agricultural areas, added with fertilizers and other chemicals at frequent intervals, is a possible cause of water pollution. The results of a study by Mishra et al. [2] suggested that the manure application based on agronomic phosphorus (P) rates may yield significant bacterial loading to downstream water bodies if rainfall occurs soon after manure application. Elevated levels of pollutants such as sediment, nutrients and heavy metals washing off urban areas impact negatively on the ecological

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health of receiving waters [3]. On disturbed soils such as on construction sites, which are prone to detachment and transport, these pollutants are often attached to sediment; however, sediment-bound pollutants can quickly become desorbed, thereby transforming into soluble pollutant forms [4]. Soluble pollutants have shown the potential to exceed 80% of the total pollutant load [5]. In case of runoff from rural watersheds, the pollutants are mainly from the residues of pesticides/insecticides/weedicides or fertilizers, or due to silt load because of soil erosion.

There is a broad range of treatment technologies available for storm water, providing a variety of benefits in terms of flood protection and targeted pollutant removal. Storm water filtration systems, which work by passing storm water through a gravel-, sand- or soil-based filter media, reduce peak runoff rates and volumes, and retain pollutants prior to discharge to groundwater or receiving surface waters [6]. Such systems are flexible in their design (ranging from large basins to small garden beds) and are particularly advantageous for urban areas, where space constraints often limit the selection of treatment techniques [7].

Kim and colleagues [8] tried novel treatment options including lignocellulose filter media and metal membranes, and found that the fibre filter media was useful to control first flush rainwater but was not enough to produce water for non-potable use in buildings. Min et al. [9] investigated the viability of base-treated juniper fibre (BTJF) media for removing toxic heavy metals (Cd^{2+}, Cu^{2+}, Pb^{2+}, Zn^{2+}) in stormwater runoff and found that the sorption ability of the BTJF for all metals was much higher than that of untreated juniper. They also deduced that there is no major headloss-related disadvantage in using BTJF instead of sand as stormwater filter media if the particle size of the BTJF is similar to that for sand. In another study, the juniper fibre was used to remove phosphorus from wastewater from a dairy farm in New York. The fibre was installed inside a filter box, forming a non-woven mat. Phosphorus removal efficiency of the fibre filter is about 41% at 59 parts per million (ppm) of inlet phosphorus concentration [10].

Johir et al. [11] used a high-rate fibre filter as a pre-treatment to stormwater in conjunction with in-line flocculation. The fibre filter effectively reduced suspended solids (98%), turbidity (95%), TOC (30–40%) and coliform (93%). The removal efficiency of nitrogen was low though the removal efficiency of phosphorous was significant. The study revealed that fibre filter can be an excellent pre-treatment to membrane filtration that may be considered as post-treatment operation. Gironás et al. [12] studied a mixed porous media composed of expanded perlite and a nonwoven needle-punched geotextile used to reduce the suspended solids load and concentration in urban runoff. They put forward laboratory procedures to quantify the suspended solids removal efficiency and the variation in time of the filtration rate.

A wide range of materials such as sand, gravel, charcoal (different types and grades), anthracite, nano-carbon, perlite, vermiculate, different types of soils such as peat, laterite, etc., furnace slag, bio-fibre materials, glass wool, fibre glass, etc. can be used as filtration media [13]. The selection of the right medium is important, as each has different hydraulic, pollutant removal and clogging characteristics.

The filter media is incorporated into the filter bed. The three key properties of the bed are its surface area, depth, and profile. The required surface area for a filter is usually based on a percentage of impervious area treated and the media itself, and may vary due to regional rainfall patterns and local criteria for water quality treatment volumes [14].

The advantages of natural fibres over synthetic or man-made fibres such as glass are their relatively high stiffness, low density, recyclability, biodegradability, renewable raw materials, and their relatively low cost [15,16]. Besides, natural fibres are generally environmental friendly and expected to give less health problems for the people producing the composites. These fibres are basically a rigid, crystalline cellulose microfibril-reinforced amorphous lignin and hemicelluloses matrix. Most plant fibres, except for cotton, are composed of cellulose, hemicelluloses, lignin, waxes and some water-soluble compounds.

Coir is a natural vegetable hard fibre extracted from the exocarp of the fruit of the coconut palm *Cocos nucifera*. It is mainly used in the manufacture of yarn, cardage and a wide range of furnishings and packaging materials. Praveen et al. [17] describe coir as 100% organic biodegradable lignocellulosic fibre and the hardest natural fibre due to its high lignin content. In the field of geotextiles, coir can be used for filtration preventing the mixing of a fine soil and a coarse material, and also for slope stabilization as it can protect a material by sharing its load and strain. It has high content of lignin which is followed by cellulose, water-soluble matter, pectic substances, ash content and hemicellulose. Mishra [18] states that the extraction of the fibres from the husk involves retting, cleaning, drying and combing. Coir is resistant to fungal and bacterial degradation. Unlike other cellulosic fibres, coir fibre is more resistant to tendering and chemical attacks.

The removal of heavy metals can be governed by any of four basic mechanisms: absorption, adsorption, ion exchange and chelation. The most probable mechanism may be ion exchange [10]. Praveen et al. [17] studied the use of coir geotextile-packed conduits for the removal of biodegradable matter from wastewater and found that it could be an acceptable solution for most small-scale wastewater treatment units. Kim et al. [19] developed a lignocellulose fibre filter medium to control heavy metals and nutrients in urban stormwater runoff and found that it is effective in treating stormwater with minimal cost and high efficiency. Biomass-based filtration media were used to remove pollutants and nutrients found in agricultural runoff [10,11,20]. Boyer [21] designed sinkhole filters for removing agricultural contaminants and assessed the removal efficiency of bacteria and nitrate. Kim et al. [8] reported that, by using a 1 μm metal membrane filter, the electrical conductivity (EC) of a mixture of greywater and rainwater could be brought down from 0.1562 to 0.1399 $dS\,m^{-1}$ (10.4% reduction efficiency). The use of tertiary membrane-filtered wastewater for irrigation as an alternative to natural freshwater sources was evaluated by Lonigro et al. [22], who found it can be considered a valid alternative source of water for vegetable crop irrigation.

The challenge faced by the designer of a stormwater filter is to find a design that will provide a sufficient flow-through rate to process most of the runoff events. The filter has to be made as small as possible for cost reasons, while large enough to pass through the design event(s) without backing up water [23]. The two basic considerations when designing any system are its hydraulic efficiency and filtration effectiveness [24]. Since these two indices are generally inversely proportional to each other, the optimum design should be evolved by considering other factors such as economics, amount and pollutant load of inlet water, target use of treated water, etc.

In this context, this study was initiated to assess the performance of a coir (coconut, *Cocos nucifera*) fibre filled multimedia sequential filter for enhancing the quality of stormwater. The process of filtration was modelled using multiple regression analysis. Furthermore, MUSIC V4 (Model for Urban Storm water Improvement Conceptualisation) developed by the Cooperative Research Centre for Catchment Hydrology (CRCCH) in Australia was calibrated and validated for the local field conditions with respect to the developed filtration system. The economic viability of the filter was also computed based on its benefit–cost ratio (BCR), net present value (NPV) and internal rate of return (IRR).

2. Materials and methods

Laboratory studies were carried out at Tamil Nadu Agricultural University, Coimbatore, India, and field studies were conducted at experimental farm belonging to the Central Plantation Crops Research Institute (CPCRI), Kasaragod, India. The former area lies between 12°13 and 12°50 north and 75°55 and 75°27 east and the latter field lies at 76° 94 east 11° north.

Input stormwater samples were collected in pre-cleaned polythene bottles with necessary precautions as per standard procedures. The water samples were further analysed for physico-chemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), total solids (TS), total hardness (TH), total alkalinity (TA), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), phosphate (PO_4^{2-}), sulphate (SO_4^{2-}), iron (Fe^{2+}), chloride (Cl^{-}) and nitrate (NO_3^{-}) using standard methods and quality assurance procedures. Another three parameters that are useful in evaluating irrigation water quality – sodium absorption ratio (SAR), residual sodium carbonate (RSC) (meq L^{-1}) and exchangeable sodium percentage (ESP) – were also calculated.

Semi-synthetic stormwater containing sediment and pollutant load with characteristics typical of stormwater runoff [25,26], was prepared in a 100 L tank by adding sieved silt (300 μm sieve), sand and fertilizers (urea, K_2O and P_2O_5) in limited quantity to the well water. The concentrations of suspended solids and chemical parameters in the dosed water were kept equal to the mean of corresponding observed values of physico-chemical parameters in storm runoff as reported by other researchers from different parts of India [27–29]. The mean chemical concentrations in a simulated runoff from a highly fertiliser and pesticide applied area were also taken into consideration while fixing the dosage of added impurities.

The particle size distribution of suspended solids used in the water samples was similar to those commonly observed in stormwater runoff. American Society for Testing and Materials (ASTM) procedure C136-96a was used to determine the particle distribution [30]. The particle size distribution of suspended solids showed that 10% of the total particles were finer than 0.05 mm in diameter, while 50% were finer than 0.1 mm in diameter and 80% finer than 0.2 mm in diameter. This dosed water was used for further filtration studies. These large dosing volumes are an exaggeration of real conditions; in effect they provide an assessment of performance under ‘near worst case’ conditions [7].

A three-chamber horizontal flow sequential multimedia stormwater filter was designed based on standard equations and procedures put forwarded by Claytor and Schueler [14] and Urbonas [31]. The dimensions of the filter were 1.5 m long, 0.6 m wide and 0.9 m deep; subsequently a dimensionally similitude model was fabricated with internal dimensions of 75 cm long, 30 cm wide and 45 cm deep, which was in 2:1 ratio with the field filter. The fabricated model was used for laboratory studies on hydraulic efficiency and quality improvement efficiencies.

Three filtration chambers with adjustable sizes could be created (Figure 1) with the help of movable screens that were bolted on a slotted rail. The filter was fabricated with 2 mm thick GI sheets. The screens, having 2 mm diameter perforations, were made up of 1.5 mm thick GI perforated sheet fixed on a 3 mm angular iron border. Screens served as a separation mechanism between various filter media (thus avoiding them getting mixed up) and also helped to retain bigger particles and physical impurities in the flowing water. Provision was made to attach textile screens in between the filter chambers replacing metal screen. Three gate valves were fitted at the inlet, outlet and backwash assembly to control the flow of water. There were provisions to measure and collect inlet and outlet water. A provision for changing the slope of the filter bed was also incorporated. The flow of water though the filter was primarily longitudinal in direction though it moves transversely along the filter depth and finally comes out through the exit pipe. There were provisions for pouring dozed water

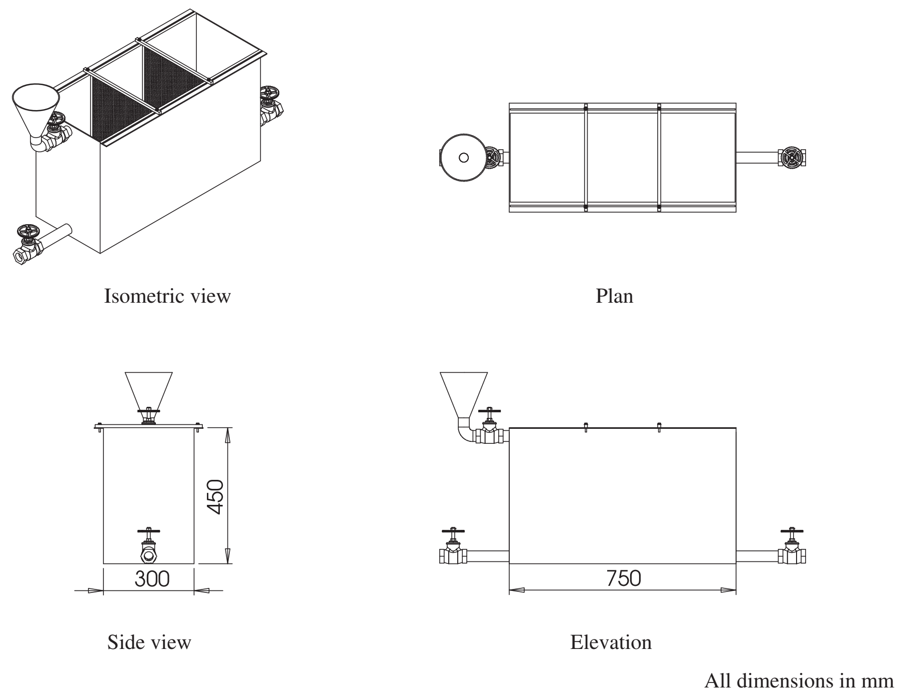

Figure 1. Plan and elevation of stormwater sequential filter.

by means of a funnel and back washing the filter at fixed intervals.

Three filter media were selected to fill up the three chambers in the multimedia filtration device. Gravel, which is a course medium (mean particle size is 20 mm) was selected as the permanent medium to be filled in the first compartment. It acts as a gross particle collector and sedimentation is the main particle removal process [32]. Similarly sand with a mean particle size of 0.7 mm and uniformity coefficient 1.46 was fixed as the filter medium for the last compartment, where finer contaminants will be separated by a solid–liquid phase separation process.

Six natural fibres (sisal, jute, hemp, coir, oil palm and banana) were tested for possible use as filter media. The superior fibre media were selected though batch and column adsorption studies based on its potential to adsorb nitrate from stormwater. For batch experiments, 50 mL of NO_3^- solution at a concentration of $100\,mg\,L^{-1}$ was put into six bottles each with 1 g of a different test medium. The mixture was equilibrated by shaking thoroughly in a mechanical shaker for different time intervals (2, 6, 18, 24, 36 and 48 hours) at $25 \pm 2\,°C$. At the end of the shaking period, the samples were centrifuged at 8000 rpm for 10 min and filtered through Whatman No.1 filter paper. The concentration NO_3^- in the extract was determined using standard methods.

The study was repeated at batch level in order to assess the solute concentration for NO_3^- adsorption. Each 50 ml of NO_3^- solution at varying concentrations (20, 40, 60, 80, $100\,mg\,L^{-1}$) were introduced into six bottles each with 1 g of a different test medium. The reaction mixture was shaken thoroughly for 24 h, centrifuged at 9800 rpm for 10 min and filtered (Whatman No. 1). The extract was then analysed for NO_3^- concentration.

A series of column experiments were further conducted to evaluate the effectiveness of various adsorbents in reducing NO_3^- concentration under a real world situation. The filter media columns were constructed by cutting six pieces of 50 mm diameter PVC pipes to a length of 45 cm. The bottom of the pipe columns was plugged and all columns were first rinsed with 100 mL distilled water and then filled with respective fibres with uniform packing density of $11.2\,kg\,m^{-3}$. Semi-synthetic water at different pollutant levels were fed from the top of each column by means of an overhead tank at uniform flow rate and the filtered water was collected after 30 seconds to six minutes of elapsed time after the inlet water started flowing through the column by means of borosilicate glass vessels kept at the bottom of the column.

Coir (*Cocos nucifera*) fibre, which was found to be a good adsorbent by batch and column adsorption studies, was used to fill the middle chamber of the multimedia filtration device. The media were filled in 1:1:1 ratio and woven sisal hemp (50:50) fabric screens were used as a separation cum screening mechanism between layers of filter media.

The experimental setup consisted of the filter device, an electric pump set that can pump slurry/sediment water, water sump and manometers. The rate of inflow was measured first by using a measuring cylinder and a stop watch. Once the outflow had stabilized, its rate of flow was measured using the same procedure. The inlet pressure and outlet pressures were measured by means of a U-tube manometer. The experiments were first completed with well water and subsequently with semi-synthetic dosed water, both collected in the tank. The filtered water samples were collected as per standard methods in plastic containers and sent for analyses. The tests were conducted at an inflow rate of 0.05 L s^{-1} and the outlet filtered water was collected six minutes after the start of each experiment. Based on the observed data, the hydraulic efficiency and filter effectiveness of each experiment were determined. The pollutant removal mechanisms of the selected multimedia filter were also studied.

2.1. Hydraulic efficiency

Hydraulic efficiency (HE) is the measure of the fraction of the incoming stream that penetrates through the filter [33]. The rate of inflow and outflow were measured in three replications and subsequently the amounts of water penetrated through and spilled over the filter were calculated as follows:

$$\begin{aligned} \mathrm{HE} &= \text{rate of outflow} \times 100/\text{rate of inflow} = (Q_{\mathrm{in}}/Q_{\mathrm{out}}) \\ &\quad \times 100 = (\text{rate of inflow} - \text{rate of spilled over water}) \\ &\quad \times 100/\text{rate of inflow} \end{aligned} \tag{1}$$

2.2. Filter effectiveness

The filter effectiveness can be expressed as the fraction of total particulates removed by the filter. For a certain chemical parameter, the average percentage removal was calculated as follows [34]:

$$\%\, R_{\mathrm{a}} = [(C_i - C_o)/C_i]100 \tag{2}$$

where R_{a} is the average percentage removal of a certain chemical parameter, C is the concentration of a certain chemical parameter, and subscripts 'i' and 'o' refer to the inlet and outlet water of the filter device, respectively (mg L^{-1}).

The same type of formulae was used to determine the EC reducing efficiency and sediment removal efficiency. However, since pH has to be brought to neutral by the filtration process, another equation is formulated to determine the pH normalizing efficiency, as given below:

$$\text{pH normalizing efficiency} = \left[\frac{pH_i - |7 - pH_o|}{pH_i}\right]100 \tag{3}$$

where pH_i is the initial pH of water before filtration and pH_o is the pH of water after filtration.

The term filter effectiveness is the mean of the R_{a} values with respect to all analysed physico-chemical parameters and the pH normalizing efficiency, and is identical to the overall quality improving efficiency (QIE), which is referred to below.

A study was conducted to determine the quantity of silt and sediments trapped inside the stormwater horizontal filter along the media and screens. For this, 10 L of sediment water with a TS content of 12 g L^{-1} was applied to the filter filled with sand medium (with metal screen). Similarly charcoal and coir fibre were used to separately fill the filter without screens and the test was repeated. The experiment was further repeated with the selected best filter combination, i.e. gravel–coir fibre–sand (GFS) with woven sisal hemp screen. The sediment trapped inside the filter was measured at different depths from the surface (0, 15, 30 and 45 cm at lengths 0, 25, 50 and 75 cm from the inlet side of the filter) so that a grid could be plotted. To calculate the trapped sediment, 10 g of the medium was taken at the specified depths, dried and weighed to determine its weight difference with the same quantity of pure fibre. The grid data were further analysed and depth profiles of media pollutant concentrations were constructed using Surfer, Golden Software, Inc., USA. Further studies were also carried out to investigate the effect of residence time and rate of flow on percentage removal of contaminants.

The filter combination was further tested and validated in the field. Field testing of the selected filter combination was carried out at CPCRI in Kasaragod. The selected area was located at mean sea level of 12 m and the soil was mainly lateritic in nature with around 10–11% impervious area. The filter system consisted of a sedimentation chamber with overflow pipes designed to skim off floatable debris and a filter with three chambers separated by screens. The filter device was constructed in such a way that the filtered water could reach the harvesting tank through a pipe conduit connected between the two structures. The filter chambers were filled such that the combination was gravel in the first chamber, sand in the last chamber and the coir fibre in the middle chamber. The media were separated by inserting a woven sisal hemp (50:50) fabric screen through the grooves provided. The media were filled up to a height of 60 cm and the remaining 30 cm was kept as extended detention depth [35].

The rate of inflow and outflow were measured using a V-notch weir. The height of water in the filter and the extended detention depth (free board) were also noted. Discrete flow samples were taken at the inlet, just upstream of the filter, and at the filter's outlet pipe as per standard procedures. The collected water samples were subjected to detailed analysis as per standard methods for determining the various physico-chemical parameters.

A multilinear regression model was developed to predict the pollutant removal process of a particular filter. This attempts to model the relationship between four explanatory variables and a response variable by fitting a linear equation. The four independent variables used for model development were input concentration (C_{in}), filter surface area (A_f), hydraulic conductivity of multi-layered media (K_f) and the hydraulic gradient (H).

Cost–benefit analyses were carried out for the filtration mechanism. Apart from BCR, NPV and IRR were also computed using standard methods.

The model MUSIC was calibrated and validated for the actual field conditions using the gravel–coir fibre–sand filter combination in a 1:1:1 ratio separated with woven sisal hemp fabric screens. MUSIC simulated the operation of the media filtration system. The default properties of the 'media filtration' node were edited to match the specifications of the filtration system being used. Such modifications were undertaken using observed climatic and land data, filter as well as media specifications, and published and peer-reviewed data. The inlet data for the treatment nodes were generally categorized as: (i) inlet properties; (ii) storage properties; (iii) filtration properties; (iv) media properties; and (v) outlet properties. The daily rainfall and evapotranspiration (ET) values of the study area for the year 2009 were also fed as the input of the model. In addition, the TSS, TP and TN of the stream flow and base flow, percentage of pervious and impervious areas, soil properties, flow rate, groundwater properties, etc. were supplied to the system as input data. The software predicted the output concentrations and generated time series graphs of pollutant removal.

3. Results and discussion

3.1. Batch and column studies

The kinetic behaviour of different fibres showed that the nitrate sorption capacity of banana fibre was almost negligible. In contrast, coir, jute and oil palm fibres showed increased sorption capacity for NO_3^-. Adsorption of NO_3^- occurred mostly within first 24 h for coir, sisal, hemp and banana, 18 h for oil palm and 6 h for jute fibres. Irrespective of the adsorbent, the adsorption percentage increased with an increase in initial concentration of the solution. The adsorption capacity of various natural fibres tested for NO_3^- adsorption followed the order: coir > oil palm > sisal > hemp > jute > banana. The NO_3^- adsorption properties of natural fibres could be adequately described by a Freundlich isotherm. Based on column studies, it was observed that in case of NO_3^- removal, coir fibre performed the best, closely followed by sisal and oil palm. The coir, oil palm and jute fibres showed the highest TS removal efficiencies. Similarly sisal, oil palm and jute performed well in terms of for reducing EC compared with the other fibres. Banana fibre was found to be less efficient in all cases. Coir fibre that showed superior performance in both the batch and column test was selected for further filtration studies.

3.2. Hydraulic performance

Hydraulic performance analysis of the gravel–coir fibre–sand filter combination in a 1:1:1 ratio separated with woven sisal hemp fabric screens was conducted at various sediment concentrations of inflow water (Figure 2). Hydraulic efficiency showed a diminishing trend as the sediment level

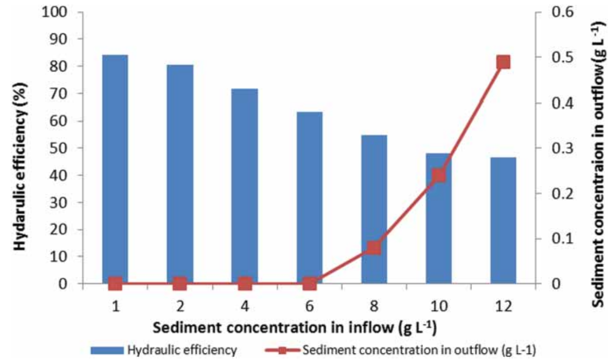

Figure 2. Effect of inflow sediment concentration on hydraulic efficiency and outflow sediment concentration.

in inflow increased. The filter exhibited 100% sediment removal at lower sediment concentrations in inflow water (>6 g L^{-1}). The sediment level in the effluent showed a linear relationship with inflow sediment concentration when the inflow concentration was >6 gL^{-1}. A considerable difference in sediment concentration in the filtered water was observed with increase in inflow sediment concentration from 6 to 12 g L^{-1}. For multimedia filtration units filled with coarse sand, gravel and pebble, the same effect has been reported with an increase in inflow sediment concentration from 10 to 16 g L^{-1} [36].

3.3. Quality improving efficiency

The filter could substantially improve the quality of stormwater passed through it. The filter could remove 45.5% NO_3^-, whereas, a study conducted in Korea by Kim et al. [19] reported only a 32% reduction in total nitrogen (TN) using a lignocellulose filter. Removal percentages of Ca^{2+}, Mg^{2+} and Na^+ were 9.28%, 39% and 31.07%, respectively. It was observed that 9.5% of Cl^- and 49.13% of SO_4^{2-} were also removed. The filter could also remove 100% of TS. Johir et al. [11] tested a filter filled with a bundle of micro-fibres and observed that it removed 94% of total suspended solids. As far as total alkalinity (TA) and total hardness (TH) are concerned, 20% and 19.2% removal efficiencies were observed. The filter also showed 97.24% efficiency in normalizing the pH and 13.27% efficiency in reducing the EC.

It appears that the filter medium not only rejects particulate matter and pollutants, but also removes soluble ions. Fibre filter media are known to remove contaminants in rainwater through ion exchange mechanisms. Three-stage filtration by means of multiple filter layers also helps to reduce the contaminants from water.

The relationship between the total chemicals in influent raw water and effluent filtered water was studied. It was observed that a linear relationship (Equation (4)) existed between chemicals in influent raw water and effluent filtered water with an R^2 value of 0.9875. The best fit equation is:

$$C_o = 0.87\,C_i + 5.84 \tag{4}$$

Table 1. Parameter wise quality improving regression equations.

Sl No.	Parameter	Quality improvement regression equation	R^2 value
1	TDS	$C_o = 0.33\ C_i + 1653$	0.9034
2	EC	$C_o = 0.33\ C_i + 2361.5$	0.9034
4	TH	$C_o = 0.72\ C_i + 234.03$	0.9465
5	Ca	$C_o = 0.72\ C_i + 65.34$	0.9546
6	Mg	$C_o = 0.73\ C_i + 18.1$	0.927
7	NO_3	$C_o = 0.32\ C_i + 76.56$	0.9119
8	SO_4	$C_o = 0.34\ C_i + 260.63$	0.9269
9	PO_4	$C_o = 0.04\ C_i - 0.0009$	0.9012

Concentration in $\mathrm{mg\,L^{-1}}$; EC is expressed in $\mathrm{dS\,m^{-1}}$.

Regression equations were developed using the dataset of inflow chemical concentration (C_i, $\mathrm{mg\,L^{-1}}$) and outflow chemical concentration (C_o, $\mathrm{mg\,L^{-1}}$) for all tested chemical parameters (Table 1). Similarly regression equations of other parameters, TS, pH and EC, were also calculated. Only equations having R^2 value >0.9 are presented in Table 1.

3.4. Sediment accumulation along depth of filter

The accumulated physical impurities, especially silt particles, gradually form a layer restricting further filtration. The degree of trapping and adsorption of suspended particles by the filter is a function of the suspended solids concentration, filter characteristics and hydraulic loading. Suspended solids removal is enhanced by longer travel distances through the filter media. If more silt and other suspended sediments are entrapped in the filter body, backwashing is required to wash out the sediments and to open up the pores in filter media and screens again. In this context, a study was conducted to determine the quantity of silt and sediments trapped inside the filter body within the media and screens. Cross-sectional profiles of sediment accumulation along the filter length are depicted in Figure 3(a)–(d).

A major portion of the sediments were accumulated at the top before the first screen for sand filter with GI screens (Figure 3(a)). Similarly silt was found to be deposited at the bottom portion of the inlet. When the test was conducted with charcoal media without inserting any screens, the maximum amount of trapped sediments was visible towards the bottom of the inlet and top of the outlet (Figure 3(b)). This could be due to the outward surge of sediments from the major flow path. For coir fibre (Figure 3(c)), the maximum sediment load was observed towards the top of the outlet. However, the sediment accumulation profile of the gravel–coir fibre–sand (1:1:1) multimedia filter with woven sisal hemp screens showed a different pattern with more particles accumulating towards the front side of the screens throughout its depth except in the flow path (Figure 3(d)).

The results obtained are in accordance with the hypothesis forwarded by Siriwardene et al. [37]. They reported that the stormwater filters that utilize coarse filter media such as

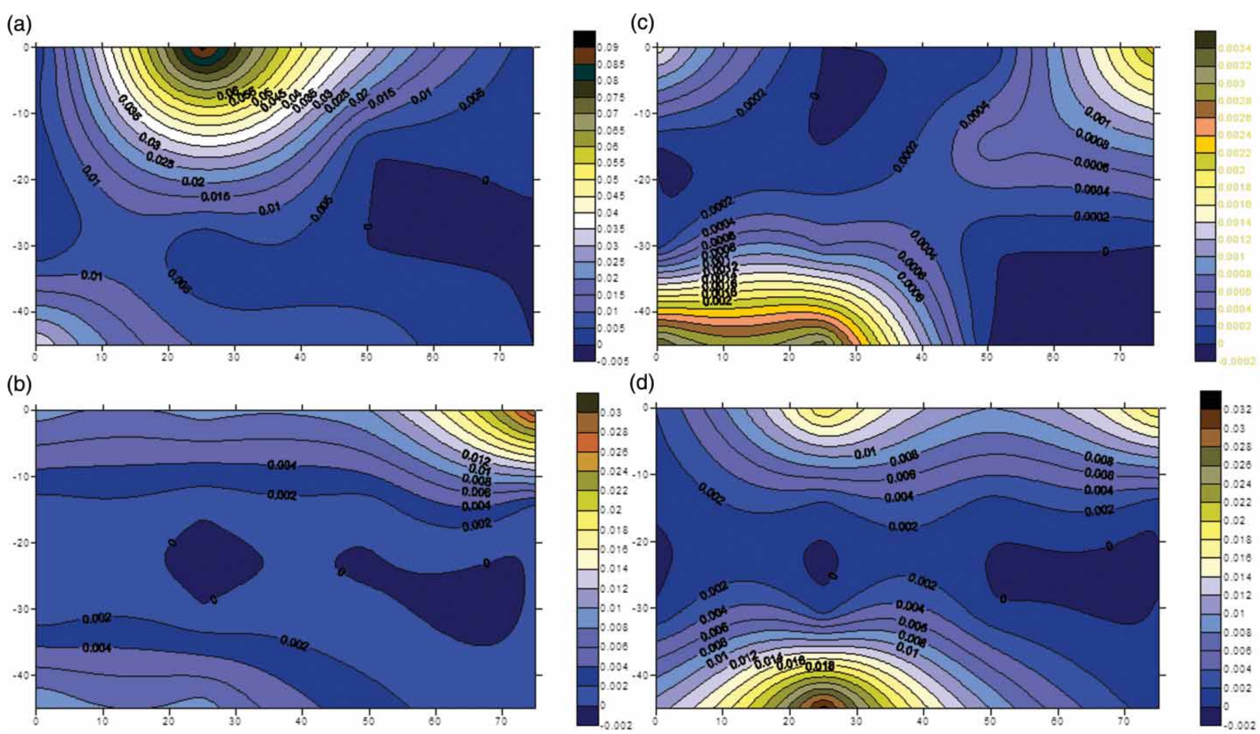

Figure 3. Profile of sediment deposition in (a) sand filled filter with metal screens (b) filter filled with shell charcoal without screen (c) filter filled with coir fibre without screen and (d) gravel–coir fibre–sand (1:1:1) filter with woven sisal hemp screen.

gravel are susceptible to clogging, as fine sediments migrate through the media and form a layer of low permeability at the bottom of the filter. This may lead to gradual filling of pore spaces, resulting in a reduction in hydraulic conductivity, which may in turn lead to a reduction in the hydraulic efficiency of the filter. While fine media systems will also get clogged, it is hypothesized that the clogging of fine media filters will be easier to manage, since the clogging layer will develop at the top of the filter and can be scraped off [30,38], as opposed to coarse media systems where clogging at the bottom of the filter [37] will require the whole filter media to be removed and replaced. In the present study, more sediment accumulated on top of the sand-filled filter, while sediment deposition was more towards the bottom for the charcoal-filled filter.

The long-term performance of textile filters depends on their degradation rate and clogging frequency in the filters under routine operational conditions. Studies performed earlier on the degradation of coir fibres had revealed that the combined effects from a variety of factors such as the type of curing, diameter of the fibre and environmental/exposure conditions initiate their deterioration [16]. A preliminary assessment made using reactors that were operated continuously for one year showed only a marginal reduction in the dry weight (less than 2%). On clogging, the stiffness of the fibres and porous matrix of non-woven coir geotextiles provided enough space for the wastewater to flow and prevented any such problems in low-density filters. However, for higher fibre packing (above 80 kg m^{-3}), continuous operation of the filters required frequent cleaning due to the formation of biological flocs in the inlet region of the reactors [17]. In the present study the packing density was limited to 33 kg m^{-3}, which ensures less clogging and free flow of water for long durations.

3.5. *Residence time*

Studies were conducted to determine the percentage removal of NO_3^- and TS for different residence times of raw water within the filter device. The results of the study (Figure 4(a)) suggested that the removal rate increases with an increase in residence time and it was more visible in the case of NO_3^- compared with TS. It was observed that the increase was sharp in the first few seconds till the water flow reached a uniform rate; the rate of increase in removal percentage then decreased. The same trend was reported by Grizzard [39]. By increasing the retention time, the filtration efficiency of contaminants, especially dissolved pollutants, could be increased.

The change in removal percentage of NO_3^- and TS with the change in rate flow within the multimedia filter was also investigated. The results (Figure 4(b)) suggested a decrease in removal percentage for TS with an increase in flow rate. But for NO_3^-, the removal percentage first increased with an increase in flow rate, then decreased and reached a constant

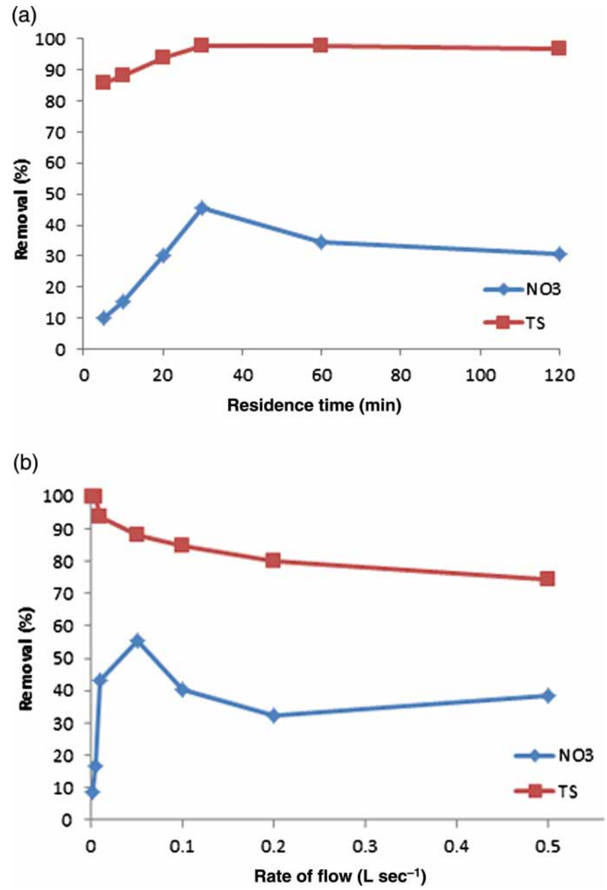

Figure 4. Change in removal percentage with increase in (a) residence time and (b) flow rate.

rate subsequently. The results obtained are in good agreement with the experimental results put forwarded by Deletic and Fletcher [40].

3.6. *Modelling of filtration process*

Creation of a mathematical model for filtration would help to design, test and improve the filter mechanism for more efficient filtration properties. In this context, an attempt was made to model the filtration process. The outlet concentration was taken as the dependent variable. Inlet concentration, filtration area, hydraulic conductivity and hydraulic gradient of the filter were the four independent variables that had an effect on the process. Multiple regression analysis was carried out to determine the relationship among the independent variables and its combined effect on the dependent variable. A multiple regression equation that mathematically represents the filtration process was thus developed and presented as follows:

$$C_o = 0.889\, C_i + 81.352\, A_f - 850.663\, K - 275.148\, i - 66.759 \quad (5)$$

($R^2 = 0.9643$)

where C_o is the outlet water concentration ($\mathrm{mg\,L^{-1}}$), C_i is the inlet water concentration ($\mathrm{mg\,L^{-1}}$), A_f is the surface area of filter bed ($\mathrm{m^2}$), K is the hydraulic conductivity ($\mathrm{m\,s^{-1}}$) and i is the hydraulic gradient (slope) of the filter

The 'p' values were found to be higher for independent variables K and i (0.168 and 0.198, respectively) and therefore having lesser predictive power of the dependent variable. It can be interpreted as if C_i, A_f and i are made to predict the output water concentration, there is 83.2% (1–0.168) that K adds to predictive power. If independent variables C_i, A_f and K are made to predict the output water concentration, there is only 80.2% chance that the independent variable i increases predictive power. But if variables A_f, K and i are made to predict the output water concentration, there is almost 100% ($1 - 1.56 \times 10^{-36}$) chance that the independent variable C_i increases predictive power, which is having a p value as small as 1.56×10^{-36}. Similarly there is 99.99% chance ($1 - 1.92 \times 10^{-6}$) that the independent variable A_f adds power to predict C_o.

The independent variables having a p value >0.15 were discarded and a new regression equation was developed involving independent variables, that were having more predictive power. Hence the modified equation for C_o, by considering independent variables C_i and A_f only is given below:

$$C_o = 0.866\,C_i + 64.243\,A_f - 58.117 \qquad (6)$$

3.7. Field evaluation of the filter

Field evaluation of the filtration system, gravel–coir fibre–sand filter (1:1:1) with woven sisal-hemp screen was conducted at CPCRI in Kasaragod. The filtration system was installed in the field incorporating a sedimentation chamber to settle pollutants before runoff reached the filter bed. The importance of settling as a pollutant removal pathway increases as more time and volume is provided for settling [14]. It was determined that 38.4% of the sediment load had been removed by settling in the sedimentation tank. For small storms, the removal percentage was as high as 69.2%, but for big storms which resulted in high runoff volume, the removal efficiency was as low as 16.65%. Removal of chemicals (if present) in the sedimentation chamber was not observed.

Hydraulic efficiency and the change in quality parameters of inflow and outflow water of the filter were assessed. The average hydraulic efficiency was found to be 69.5%. As observed in the laboratory studies, the hydraulic efficiency reduced rapidly with an increase in flow rate above $1\,\mathrm{L\,s^{-1}}$ due to spilling over of water above the filter. The change in water quality parameters by field filtering process is shown in Table 2.

The removal efficiencies obtained in the field test resembled those from the laboratory, except in the case of Ca^+ and EC. It was observed that the concentrations of Ca^+ and K^+ were increased by filtration and this phenomenon could be attributed to the preferential leaching effects from biofibres containing K^+ and Ca^+. The high concentration of Ca observed in the outlet water from the field filter might be due to the leaching out of Ca salts into flowing water from the walls of the filter coated with white cement having high percentage of $CaCO_3$. The increase in EC may also be attributed to the increase in number of ions due to release of chemicals such as $CaCO_3$. However, the reduction in total solids (TS) was higher than the lab average with almost 90% reduction in sediment load. The change in colour is a direct indicator of the reduced turbidity, which in turn was due to decreased amount of total suspended solids (TSS). The pH normalizing efficiency (98.5%) recorded was also high. The removal percentages of Mg and Na were in good agreement with the laboratory results, but higher removal efficiencies were recorded for NO_3^- and SO_4^{2-}.

Pollutant concentration in output water was predicted using the model (Equation (7)) and subsequently compared with the observed values by means of Chi-squared test:

$$\chi^2 = \Sigma[(\text{Observed} - \text{Expected})^2/\text{Expected}] \qquad (7)$$

Small values of chi-square statistics indicate a good model and in this case, the obtained χ^2 and the p values were 3.311 and 0.769, respectively. The values suggest no significant difference between the expected and observed result, and that therefore the developed multi-regression model can be used to predict filter performance and output water quality in real world situations.

3.8. Economic analysis and environmental compatibility of filtration systems

Benefit–cost analysis of the developed filters was performed to determine its economic feasibility. Fixed and variable costs along with annual returns of the stormwater filter were calculated (Table 3). The cost of filtration per cubic metre

Table 2. Change in water quality parameters by field filter.

Parameter	TS*	EC**	pH	Ca^{2+}***	Mg^{2+}***	K^+***	Na^+***	NO_3^-***	SO_4^{2-}***
Before filtration	15.59	0.0683	6.45	8.1	4.76	4.8	16.4	42.8	55.4
After filtration	1.61	0.1044	6.91	12.14	3.23	6.43	10.86	14.4	12.2
Treatment Efficiency	89.7	−52.9	98.54	−49.8	32.13	−33.94	33.8	66.36	77.98

*Concentration in $\mathrm{g\,L^{-1}}$; **EC is expressed in $\mathrm{dS\,m^{-1}}$; ***Concentration in $\mathrm{mg\,L^{-1}}$.

Table 3. Details of fixed and variable costs, returns, NPV, IRR and BC ratio of the horizontal storm water filter system.

	Particulars	Economic life (years)									
		1	2	3	4	5	6	7	8	9	10
A	**Fixed cost** (INR*)										
	Rental value of land (INR/year for $2\,m^2$)	50	50	50	50	50	50	50	50	50	50
	Cost of gravel filter medium ($0.27\,m^3$ @ INR $800/m^3$)	216									
	Cost of construction of water filter structure with sedimentation chamber including pipe fittings	6760	0	0	0	500	0	0	0	0	0
	Sub-total	**7026**	**50**	**50**	**50**	**550**	**50**	**50**	**50**	**50**	**50**
B	**Variable cost** (INR)										
	Cost of coir fibre filter medium (9 kg @ INR 15/kg) considering replacement monthly	1620	1620	1620	1620	1620	1620	1620	1620	1620	1620
	Cost of sand filter medium($0.27\,m^3$ @ INR $1750/m^3$) considering replacement twice per year	945	945	945	945	945	945	945	945	945	945
	Miscellaneous and maintenance costs	200	200	200	200	200	200	200	200	200	200
	Sub-total	**2765**	**2765**	**2765**	**2765**	**2765**	**2765**	**2765**	**2765**	**2765**	**2765**
C	**Total cost (A+B) in INR**	**9791**	**2815**	**2815**	**2815**	**3315**	**2815**	**2815**	**2815**	**2815**	**2815**
D	**Returns (INR)**										
	Water quality improvement – Cost of water filtration (INR $1.5/m^3$ for $4682\,m^3$ of stormwater annually)	7023	7023	7023	7023	7023	7023	7023	7023	7023	7023
	Salvage value	0	0	0	0	0	0	0	0	0	700
	Reduction in maintenance & repair of pump and irrigation systems		500		500		500		500		500
E	**Total return** (INR)	**7023**	**7523**	**7023**	**7523**	**7023**	**7523**	**7023**	**7523**	**7023**	**8223**
F	**Net return (E − C) in** INR	**−2768**	**4708**	**4208**	**4708**	**3708**	**4708**	**4208**	**4708**	**4208**	**5408**
	NPV (INR)	**16977.971**									
	IRR	**165%**									
	BCR	**1.8060816**									

*USD 1 = INR 44.3

Table 4. Cost of filtration, NPV, IRR and BCR values of the filter in Indian rupee (INR*).

Type of filter	Cost of filtration/m^3 (INR)	NPV (INR)	IRR (%)	BC ratio
Stormwater	0.76	16978.00	165	1.80608

*USD 1 = INR 44.3

of water, NPV, IRR and BCR of the filter were computed (Table 4).

NPV was observed as positive and IRR was greater than the considered discount rate (14%). Moreover, the BCR showed a value greater than 1, which is acceptable. The NPV (INR 16,978) and BCR (1.81) of the stormwater filtration system indicate that establishing such a filter device is highly profitable and an attractive investment proposal. The cost of filtration was as low as INR 0.76 per m^3 of stormwater. Santhi et al. [41] reported a BCR of 4.3 for water quality improvement by implementing the National Conservation Buffer Initiative goal of two million miles (US Department of Agriculture), whereas Jeulanda and Whittington [42] reported a BCR for bio-sand filters at average parameter values as 2.93.

The developed filtration systems are recommended from an economic point of view, being a low-cost technology requiring low initial expenditure, zero power requirements, no maintenance costs and self-dependent operation. They are suitable for areas where there are normal seasonal rains.

Fibre media and screens made out of natural fibres were used in this study. The major advantage of natural fibres as filter media and screens over synthetic fibres is their biodegradability. Their relatively high stiffness, heavy and coarser structure (a desirable property in composites) helped to make different composite fabric filter screens, both woven and non-woven. Their low density, hygroscopic and non-hazardous nature, recyclability and relatively low cost made them a more attractive choice as

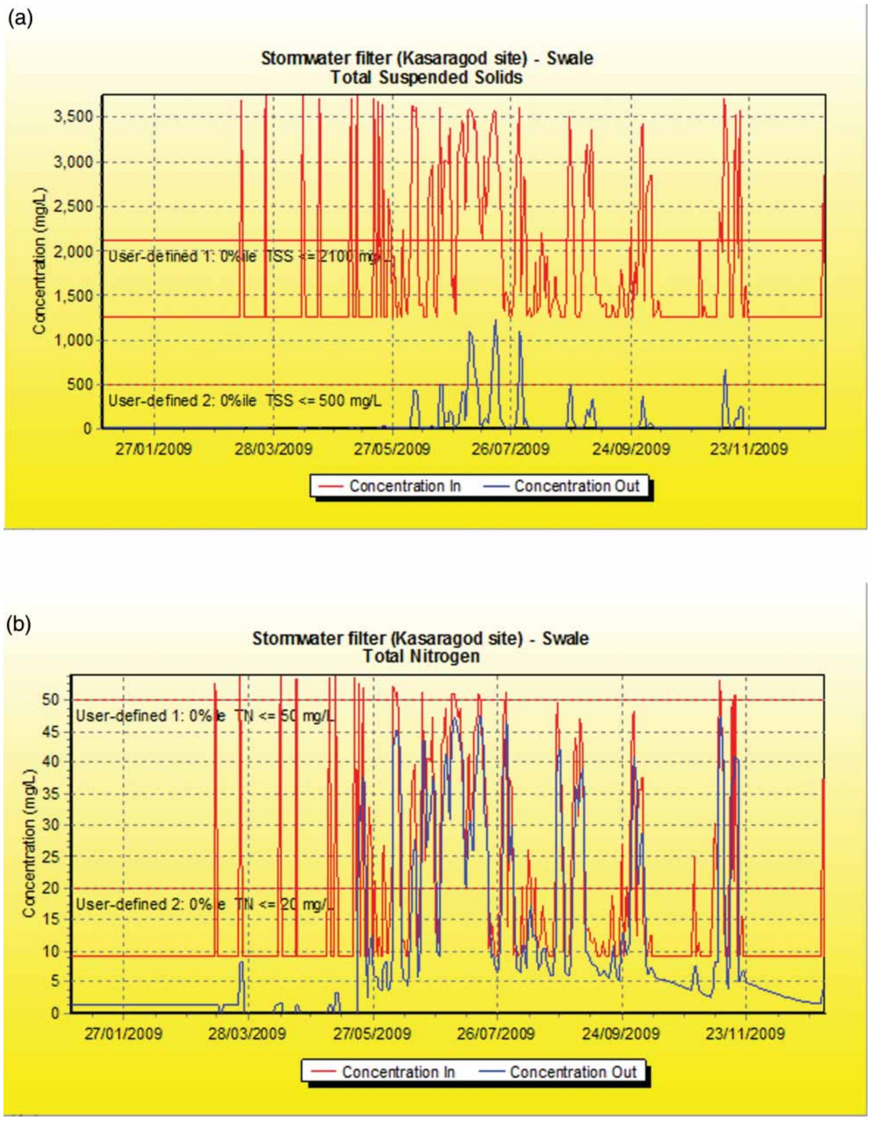

Figure 5. Time-series graph of (a) TSS and (b) nitrogen removal by horizontal multimedia (GFS) stormwater filter at Kasaragod site.

filtration media and screens. Furthermore, the raw materials used are generally readily available and renewable in nature. In addition, natural coir fibres that are clean and non-carcinogenic are expected to give less health problems for the people producing the composites. In general, it could be inferred that the natural fibre filter media and screens used in this study were essentially environmentally friendly products.

3.9. Calibration and validation of MUSIC model

The model MUSIC was calibrated and validated for actual field conditions with respect to the stormwater filter. The first step was to develop the time-series graph for rainfall and ET of the tested site (Kasaragod) for the year 2009. Subsequently, the water quality standards were specified as per World Health Organization/Bureau of Indian Standards and Indian Central Pollution Control Board guidelines [43–46]. As the next step, the source node, treatment node(s) and other nodes (receiving or junction) were selected based on the type of area, inlet water and filtration mechanism used. Details such as percentage of impervious area, soil and groundwater properties, mean concentration of TSS and chemicals in the inlet water and base flow with its standard deviation and filter details including dimensions, properties of media, etc. were fed as input. The time series curves of TSS and nitrogen removal are shown in Figures 5(a) and 5(b), respectively.

The MUSIC model predicted 77.09% removal for TSS and 40.3% for nitrogen, whereas the observed removal percentages in the field were 89.7% and 66.36%, respectively. However, the observed mean removal percentages for TSS and nitrogen obtained by multiple laboratory tests were 83.2% and 33.48% respectively, which were closer to the predicted value.

4. Conclusions

Although rainwater harvesting has been construed as the most sustainable method for managing water scarcity situations, incorporating all type of water demands, no hydraulically efficient, environmentally compatible and cost-effective filtration mechanisms are currently available for quality enrichment of rainwater in its various forms. In this context, a multimedia horizontal stormwater filter with gravel–coir fibre–sand (1:1:1) filter media separated with woven sisal hemp fabric screens was designed. Subsequently, lab models with dimensional similitude to the designed filters were fabricated and tested for hydraulic efficiency and pollutant removal efficiency. A full-scale version of the model was constructed and evaluated in the field. Hydraulic efficiency and quality improving efficiency of all filter combinations, both in laboratory and *in situ,* were evaluated.

Hydraulic analysis of the filter was conducted at various sediment concentrations of inflow water. Hydraulic efficiency showed a diminishing trend as the sediment level in inflow increases. The multimedia stormwater filter system separated by fabric screens was excellent in removing sediments, and fair in reducing sulphate, nitrate, magnesium and sodium concentrations. However, it performed comparatively poorly in removing chloride and calcium and in reducing total hardness and alkalinity. The filter not only rejects particulate matter and pollutants, but also removes soluble ions.

A study was conducted to determine the quantity of silt and sediments trapped inside the filter body within the media and screens. A major portion of the sediment accumulated on the top before the first screen for sand filter with GI screens. When the test was conducted with charcoal media without screens, maximum trapped sediment was visible towards the bottom of the inlet and the top of the outlet. For coir fibre, the maximum sediment load was observed towards the top of the outlet. However, the multimedia filter with screens showed a different pattern with more particles accumulating towards the front side of the screens throughout its depth except in the flow path. Stormwater filters utilizing coarse filter media such as gravel are susceptible to clogging, as fine sediment migrates through the media and forms a layer of low permeability at the bottom of the filter. For fine media systems, the clogging layer will develop on the top of the filter.

Studies were conducted to determine the percentage removal of NO_3^- and TS for different residence times of raw water within the filter device. The removal rate increased with an increase in residence time and it was more visible in the case of NO_3^- than TS. The change in removal percentages of NO_3^- and TS with the change in rate of flow was also studied. The results suggested a decrease in removal percentage for TS with an increase in flow rate. But for NO_3^-, the removal percentage first increased with an increase in flow rate, then decreased and reached a constant rate subsequently. A multiple regression equation that mathematically represents the filtration process was also developed.

The field evaluation of the filter showed 97.24% efficiency in normalizing pH and 13.27% efficiency in reducing EC. The removal percentages of Mg and Na were in good agreement with the laboratory results. High removal efficiencies were recorded for TS, NO_3^- and SO_4^{2-}.

The NPV (INR 16,978) and BCR (1.81) of the stormwater filtration system indicate that establishing such a filter device is highly profitable and an attractive investment proposal. The costs of filtration per cubic metre of stormwater was only INR 0.76. The natural fibre filter medium and screens used in this study were cheap, environmentally compatible, biodegradable, commonly available and renewable in nature.

The model MUSIC was calibrated and validated for field conditions with respect to the stormwater filter. Time series curves for pollutant removal were developed. The model predicted TSS and N values in the outflow water that were reasonably closer to the observed values. The MUSIC software is useful tool in predicting output concentrations of a particular filter system for specific special and temporal conditions.

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