LITERATURE REVIEW

Natural or artificial water conveyance structures possessing free surface exposed to the uniform pressure are referred to as open channels. They include rivers, streams, irrigation furrows and canals. Canals are manmade and are extensively used as a major means of delivering water to the distant places for various purposes such as irrigation, water supply, flood control, etc. These structures carry water over hundreds of kilometres, and thus make the irrigation project to be a costly affair. Significant research efforts have been put to design these canals for improved performance and reduced cost. A comprehensive review of the relevant literature was carried out to assess the scope of the further investigation into the area of optimal design of channels. The following sections are devoted to analyze the gap in the available knowledge base.

2.1 Channel Geometric Shape

Several geometric shapes are available for the design of channels. These shapes are either a simple geometrical shape such as triangular, rectangular, trapezoidal, semicircular, or the geometric shapes obtained by putting simple geometric shapes together such as U- shaped, horizontal bottom with parabolic sides etc. Among all these shapes, the parabolic canals evoked the highest interest among the several researchers (Mironenko et al. 1984; Flynn and Marino 1987; and Loganathan 1991). Mironenko et al. (1984)

claimed that parabolic canal sections are advantageous because parabolic sections are close to the shape of natural channels (Monadjemi 1994). Loganathan (1991) also designed a hydraulically efficient optimal parabolic canal section accounting for freeboard with limitations on velocity and canal dimensions. He demonstrated that for parabolic channels the optimum maximum side slope is 0.514:1(horizontal:vertical).

Monadjemi (1994) applied Lagrange's method of undetermined multipliers to determine the best hydraulic section. Froehlich (1994) also applied Lagrange technique to determine the best trapezoidal section with width and depth constraints. Babaeyan-Koopaei et al. (2000) designed a parabolic-bottomed triangle cross section for maximum hydraulic efficiency using Lagrange undetermined multipliers method. He showed that the flow area and wetted perimeter of parabolic-bottomed triangle cross section are less than those of trapezoidal and parabolic cross sections for the same discharge, they concluded that their section would need less excavation and linings, hence turned out to be more economical than trapezoidal and parabolic cross sections. Willardson (1988) also stated that the riverbeds, unlined canals, and irrigation furrows all tend to approximate a stable parabolic shape, therefore, Mironenko et al. (1984) stated that the unlined canals can be made more hydraulically stable by constructing them in a parabolic shape from the beginning. Anwar and de Vries (2003) designed a power-law channel that included parabolic and triangular cross sections. They applied a series expansion (power index less than 0.5) and a non-linear interpolation expression (power index more than 0.5) to determine the wetted perimeter of the section, and used Lagrange method of undetermined multipliers to minimize the area and/or wetted perimeter for a given maximum side slopes. The features of the optimized power-law channels were analyzed in relation to the trapezoidal and parabolic channels and existing parabolic design of the Pehur High Level Canal, Pakistan. Chahar (2005a) designed a parabolic canal section for a minimum earthwork and lining costs. He applied Fibbonaci search method on a nonlinear unconstrained optimization problem by imposing bounds on the canal dimensions and the velocity of flow to obtain an optimal section.

Open channels are normally designed with a freeboard to provide a factor of safety against the conditions that may cause the water surface in the channel to exceed the design flow rate. Such conditions may arise due to waves, wind, sedimentation, or even by increased roughness of the constructed channel. Anwar and Clarke (2005) designed a power-law channel that had a variable exponent for maximizing the cross-sectional area or minimizing the wetted perimeter for achieving the maximum permissible side slopes. The variable exponent allowed a rather more hydraulically efficient open channel than that of the one having a constant power exponent. Absence of freeboard in the design of a channel was criticized by Atmapoojya and Ingle (2002), therefore, they accounted freeboard in design of power-law channels.

They determined the value of optimum exponent applying Lagrange's method of undetermined multipliers. Das (2007b) investigated a channel cross section having a horizontal bed and two parabolic sides. He applied Lagrange multiplier technique to determine the geometric dimensions of the channel to minimize the construction cost. The design constraints included unrestricted, and constrained flow depth, side slopes, and top width to convey a given design flow rate. He also considered a fixed freeboard, and depth-dependent freeboard cases for the design. He claimed that his proposed cross-sectional shape captured all desirable attributes of trapezoidal and parabolic shape channels. The depth dependent freeboard equation proposed by Das (2007 b) is adopted in the present study to generate several freeboard scenarios. To reduce the land acquisition costs, the top width constrained optimal design is used Froehlich (1994). Das et al. (2001) developed procedures for design of non-silting and non-scouring parabolic channels using Lacey's (1929) and Kennedy's (1895) regime concepts.

Bandini (1966) considered the seepage loss in the channel design and compared the economy of the lined and unlined channels. Kacimov (1992) obtained optimal trapezoidal and rectangular channels for the minimum seepage loss. Explicit equations for the design of optimal polygon channels were given by Chahar (2005b) and Swamee et al. (2000a,b; 2001a,b; 2002a, b) by including seepage loss term in objective functions. Swamee and Kashyap (2001, 2004) proposed equations for the minimum seepage loss nonpolygon channels. Hunt (1972) gave an approximate solution for the seepage from a shallow channel of arbitrary cross section. Verigin (Kovacs 1981) analytically determined an approximate solution for a semicircular channel cross section in terms of a rapidly converging series. Applying an inverse boundary value method, Ilyinskii and Kacimov (1984) determined the optimal shape of a curved irrigation channel for the minimum seepage loss. Chahar (2007a) designed a curvilinear bottomed channel by minimizing the flow area and seepage. He imposed constraints on the flow velocity and channel dimensions, and found that the perimeter of the curvilinear bottomed channel fell between an ellipse and a parabola of the same top width and flow depth. He clearly stated that seepage loss might also occur in lined canals due to cracks in the lining (caused by settlement of the subgrade), weed growth and construction defects in the lining, use of inferior quality lining materials, and weathering etc. Thus, the seepage from a lined canal may reach the quantity of seepage somewhat equal to the unlined channels. Therefore, it seems appropriate to adopt earthen channels that are relatively cheaper. Chahar et al. (2007c) applied Lagrange method of undetermined multipliers to determine optimal design equations for a parabolic channel section with freeboard. He defined a channel section to be the best hydraulic section that possess the minimum wetted perimeter for a given flow area for carrying the maximum discharge. Thus, the best hydraulic section needs to maintain the maximum flow velocity or the minimum flow area and wetted perimeter for a given discharge and channel bed slope.

Several researchers (Monadjemi 1994; Swamee 1995; Froehlich 1994; Atmapoojya and Ingle 2001, 2003; and Chahar 2007) have applied Lagrange's method of undetermined multipliers for determining the best hydraulic section. Chahar and Basu (2009) designed optimal circular and parabolic bed trapezoidal canal sections by involving earthwork and lining costs in objective function. They applied Lagrange's method of undetermined multipliers for the minimum area section and MS Excel solver for the minimum cost sections. Easa (2011) proposed two-segment parabolic sides and horizontal bottom section and found it to be more economical than the trapezoidal cross section. He minimized the total construction cost that included excavation and composite linings costs. Several other optimal designs of channels were proposed such as reliability based designs (Easa 1992, 1994), hydraulic efficiency based designs (Froehlich 1994; Monadjemi 1994), designs using composite roughness method (Das 2000), designs for critical flow condition (Bhattacharjya 2006), flood probability based design (Das 2007a), and side slope stability based designs (Bhattacharjya and Satish 2007). Hussein (2008) designed a power-law channel section. He showed that the exponent and side slopes at the water surface level have values of 0.314 and 0.352, respectively. His optimal solution also demonstrated that the most hydraulically efficient power-law channel sections come closest to the semicircle in shape.

2.2 Seepage Losses

Seepage loss is another problem that earthen canals suffer. Seepage through canals cannot be controlled completely. Normally, canals are lined to check the seepage but canal lining deteriorates with time; hence, significant seepage losses continue to occur from a lined canal (Wachyan and Rushton 1987). It was estimated that the seepage losses through the earthen channels were of the order of 45% of the water supplied at the head of the canal (Sharma and Chawla 1975). Indian Standard also mentioned that the seepage loss through unlined canals in India generally varies from 0.3 to 7.0 m^3/s per million square meters of wetted surface area (Shukla and Mishra 1994; Indian Standards I.S. 9452). The transit losses are more serious in alluvial canals. Sharma and Chawla (1975) estimated that about 6,000,000 ha of area would have been irrigated additionally, if the seepage loss were prevented. An examination of canals by Wachyan and Rushton (1987) indicated that even with the greatest care the canal lining does not remain intact. A well-maintained canal with a 99% perfect lining reduces seepage about 30–40% (Wachyan and Rushton 1987).

Kilic and Tuylu (2011) determined the conveyance losses of the concrete-lined main, secondary and tertiary channels in the Right Bank Irrigation System of the Ahmetli Regulator in the Gediz Basin, Turkey. Average seepage losses were measured to be 107.6 L/s/km for the main canal, 32.1 L/s per 100m for the secondary canals, and 11.7 L/s per 100m for the tertiary canals. Standard deviation and variation coefficients were found to be 79 L/s/km and 73%, respectively, for the main canal, 29 L/s per 100m and 89%, respectively, for the secondary canals, and 17 L/s per 100m and 158%, respectively, for the tertiary canals. Hotchkiss (2001) developed a procedure for trapezoidal canal sections underlain by clay with a layer of more permeable material at depth to quantify seepage losses through unlined canals for the stretches of the order of 100 ft (30 m). His presumed conditions prevailed throughout much of the Central Nebraska Public Power and Irrigation District (Central) canal system. It has been estimated that 70% of all worldwide freshwater use is for irrigation. The off-farm conveyance efficiency in the United States was estimated to be approximately 78% [Interagency Task Force (ITF) 1979], and conveyance losses account for 1 billion L/day), which is more than 10 times the total U.S. domestic water use (Herschy and Fairbridge 1998). It was also estimated that a total of 62% of canal water was lost to seepage (CH2M-Hill 1991) before the key reaches of the Central Nebraska Public Power and Irrigation District (Central) canal system were lined in 1975. Seepage losses from unlined canals have also been estimated to range from 15 to 45% of total diverted water volume (Van der Leen et al. 1990). Swamee et al. (2000b) gave algebraic equations for computation of seepage losses from triangular, rectangular, and trapezoidal canals. They applied their equations for optimal design of minimum seepage loss canal sections and stated that the seepage loss from a canal in an unconfined flow condition is finite and maximum when the water table lies at a very large depth. Seepage losses have also been estimated by several other researchers (Harr 1962; Polubarinova- Kochina 1962; Morel-Seytoux 1964; Garg and Chawla 1970; Subramanya et al. 1973; Sharma and Chawla 1979; Wolde-Kirkos and Chawla 1994) under different conditions. An exact mathematical solution to unconfined steady-state seepage through a trapezoidal canal in a homogeneous isotropic porous medium of large depth was given by Vedernikov (Harr 1962). The solution was obtained using inversion of the hodograph and conformal mapping technique. Rao and Sitaram (1999) experimentally investigated seepage effects on the stability, mobility, and incipient motion of sand-bed particles. They stated that seepage through a sand bed in a downward direction (suction) reduces the stability of particles, and can even initiate their movement. Apart from causing loss of water, literature reveals that that seepage can significantly alter hydrodynamic and sediment transport characteristics of the alluvial channel. Bruch (1966) and Bruch and Street (1967a, b) gave an analytical solution for seepage from a triangular canal in a soil layer of finite depth overlying the drainage layer. Muskat (1946) and Vedernikov (Harr 1962) presented an approximate solution for a trapezoidal canal. Swamee et al. (2001a) proposed simplified algebraic equations to compute the seepage from triangular, rectangular, and trapezoidal canals when a drainage layer lies at shallow/ finite depth. They applied inverse hodograph and conformal mapping to give an analytical solution for the quantity of seepage from a rectangular canal underlain by a drainage layer at shallow depth. Applying the solution for the rectangular canal and the analytical solutions of triangular and trapezoidal canals, algebraic equations for computation of seepage loss through these canals were given for the condition when the drainage layer lies at finite depth. Swamee and Kashyap (2001) gave design variables for minimum seepage loss of circular and exponential canal sections. Swamee et al. (2002) further gave design equations for the least-cost canal sections considering earthwork cost, cost of lining, and cost of water lost as seepage and evaporation from irrigation canals of triangular, rectangular, and trapezoidal shapes that passed through a stratum underlain by a drainage layer at shallow depth. Giving an example of a transmission canal in Rajasthan that has length of 204 km with discharge capacity of about 524 m^3/s (Kanwar Sain 1967; Hooja 1993), they gave equations for computation of the optimal subsection length and corresponding cost of a transmission canal. They applied least-cost section equations and Fibonacci search method.

Morel-Seytoux (1964); Bandini (1966), Ilyinsky and Kacimov (1984), Kacimov (1992; 1993), Swamee et al. (2000 b, c, 2001a), and Chahar (2000) gave canal design methods for minimizing seepage loss. Chahar (2006) applied an inverse method to obtain an exact solution for seepage from a curved channel whose boundary mapped along a circle onto the hodograph plane. The solution involves inverse hodograph and Schwarz-Christoffel transformation. Kozeny (Harr 1962; Polubarinova-Kochina 1962; Muskat 1982) investigated the seepage loss from a curved channel using Zhukovsky's function and found that the resultant channel attained a trochoid shape. Anakhaev (2004) gave a solution for curvilinear channel section by representing the channels profiles in the Zhukovsky plane by means of the equation of a family of lemniscates and by using the conformal mapping. He showed that a special case reduces to Kozeny's trochoid shape. Hunt (1972) gave an approximate solution for seepage from a shallow channel of an arbitrary cross section. Verigin analytically found an approximate solution for a circular section in terms of a rapidly converging series (Kovacs 1981; Aravin and Numerov 1965). Kacimov (2003) pointed out the mistake in Verigin's solution. Ilyinskii and Kacimov (1984) proposed the optimal shape of a curved channel by minimizing the seepage loss using the inverse boundary value problem method. Furthermore, Kacimov and Obnosov (1993) applied the inverse method along with hodograph and conformal mapping to find the shape of a soil channel of constant hydraulic gradient. Swamee and Kashyap (2001) obtained seepage from nonpolygon canals using the finite difference method. Using an inverse hodograph and a Schwarz-Christoffel transformation, Chahar (2007b) gave an exact analytical solution for the quantity of seepage from a trapezoidal channel underlain by a drainage layer at a shallow depth. Hamdy et al. (2003) mentioned that water use efficiency in irrigation sector is very poor (not exceeding 45%) with more than 50% water losses. Adarsh (2012) designed different canal geometries for the minimum seepage losses. Lu et al. (2008) investigated how turbulence intensities, bed shear stresses and bed particle stability change in the presence of seepage. Their review revealed that the seepage affects the mean flow velocity distributions. The channel under design consideration also comprises permeable beds in the form of sand particles and gravels similar to the natural streams. These permeable boundaries permit mass and momentum transfer across the interface between the fluid and porous media. Although the seepage losses are not desirable but this interaction between the flow in main channel and groundwater or hyporheic exchanges allows the transport of contaminants, and thus becomes conducive to maintain a healthy stream ecosystem (Brunke and Gonser, 1997; Jones and Mulholland, 2000). However, the hydrodynamic processes in such a physical system change the structural features of the flow, which, in turn, modify the flow-resistance, sediment entrainment characteristics and morphology of the streambed as well. Although the problem of optimal design of riprap riveted earthen channel is affected by the seepage losses but this aspect has not been covered in the present study. The seepage phenomenon also affects the erosion process which is another issue in design of earthen canals.

2.3 Boundary Shear and Flow Resistance

In order to avoid the erosion of the side slopes of the canals, several measures such as riprap (with or without wire cages), vegetation, gravel, straw with net, curled wood mat, jute net, synthetic mat, fibre glass roving are often used to provide protection against the erosion in earthen channels. These linings are relatively cheap and offer several advantages, such as, providing conducive environment for the growth of flora and fauna, flourished biological species, less construction time, and ground water recharge capability. In addition to the application of the flexible linings for construction of a designed channel, the flexible linings such as vegetation and riprap (Froehlich 2011a) have also been used during operational stage of the canals to stop erosion of the side banks. The types of riprap stones possess varying characteristics, and therefore their application requires them to be designed for shape and size both. Froehlich (2011a) mentioned that open graded riprap stone can be applied to protect the banks and beds of open drainage channels from erosion.

The optimal channel design problem of the present study involves the use of riprap stone as it provides excellent protection that costs little in comparison to other types of linings (Froehlich and Benson 1996). These riprap stones also offer a visually appealing solution to erosion problems [National Stone, Sand and Gravel Association (NSSGA) 1991]. Froehlich (2011b) conducted experiments involving 74 stockpiles of natural and crushed stone and classified them into three categories based on the mass angle of repose data. These open-graded riprap stones have a narrow range of particle sizes and they result in a relatively larger void spaces within the heap. These rock mass when dumped into place, the maximum inclination of a covered slope cannot exceed the mass angle of repose of the stone. The data on mass angle of repose is also applied to calculate the size of rock riprap required to protect channel side slopes from erosion by water currents and waves (Vanoni 1977, pp. 106–107; Maynord et al. 1989; Brown and Clyde 1989; U.S. Army Corps of Engineers (USACE) 1994, p. 3-5). However, they affect the flow resistance in channels. Hey et al. (1986) gave regime type equations for mobile gravel-bed rivers. They defined gravel-bed rivers as a natural conveyance system in which hydraulic processes are controlled by material coarser than 2 mm in size. They found that gravel-bed rivers possess a significantly different hydraulic geometry than those carrying fine grained sandy material. In fact, gravel-bed rivers are characterized by macro bed forms, pools and riffles, and the general absence of smaller scale ripple, dune and antidune features, therefore, surface roughness characteristics of gravel-bed rivers vary significantly, which, in turn, influence the flow rate and bed load transport capacities of these rivers. Therefore, flow rate through the canals will be also be influenced by the carriage of sediment-laden flow. Paudel et al. (2013) stated that the sediment transport aspects are not included in the design process of canals while flow control operations in the canals carrying sediment laden flow significantly affect their hydrodynamic performance (Munir et al. 2012). Therefore, canals carrying sediment laden flow need additional care during flow control operations. Thus, the impact of sediment-laden flow needs to be accounted while designing a channel.

Maynord (1995) proposed a design procedure for sizing gabion mattresses (riprap stones encaged in a wire mesh) applied for the protection of side slopes. His provisions indicated that cross-sectional shape, channel alignment, and side slopes affect the gabion-mattress rock size and thickness as well. The reason for this impact seems to associate with the significant change in the hydraulic resistance caused by the changed flow patterns with application of gabion mattresses. Therefore, application of riprap on side slopes of a channel needs to be treated sensibly while determining the flow rate through the channel. Rouse (1965) pointed out that cross-sectional shape, boundary nonuniformity, and flow unsteadiness, fluid viscosity and wall roughness significantly affect the hydraulic resistance in open channels. Yen (2002) further discussed the differences between momentum and energy resistances between point, cross-sectional and reach resistance coefficients, as well as compound/composite channel resistance. Rouse (1965) categorized the flow resistance in channels into four components, namely, form resistance or drag, surface friction, resistance associated with local acceleration or flow unsteadiness, and the wave resistance from free surface distortion. The application of riprap on side slopes of a channel normally influence all these components, hence a significant change in the flow characteristics will alter the flow rate through the channel. Yen (2002) mentioned that the Chezy formula has the simplest form with its longest history but Manning's roughness coefficient has an advantage of being nearly a constant value for a given surface roughness characteristic of a channel. He also mentioned that it is almost independent of flow depth, Reynolds number or dimensionless roughness height for fully developed turbulent flow over a rigid rough surface. Unlike Manning's roughness coefficient, Chezy's constant C has no generally recognized table or figure for its value. Therefore, Manning's equation can be a preferred option with roughness coefficient not significantly impacted by flow characteristics.

The channel design problem that is under consideration turns out to be a composite channel since its wall roughness changes along the wetted perimeter of the cross section area, therefore, the local point wall shear and resistance shall also vary along its wetted perimeter. The channel under consideration is also a compound channel as it consists of subsections of different defined geometric shapes put together. Therefore, the channel under design consideration will act similar to the field situations (the case of main channel with floodplains) where compound channels are also composite. Three publications that augment this guide are Barnes (1967), Chow (1959), and Ree (1954). A significant research has been done to determine roughness coefficients for open-channel flow (Carter and others, 1963) but less has yet been done for densely vegetated flood plains (Yen 2002). Klopstra et al. (1997) proposed an analytical model for open channel flow with submerged vegetation. Huai et al. (2009b) applied a three-layer model for open channels with rigid vegetation, and divided the flow regime into an upper non-vegetated layer, an outer layer and a bottom layer within vegetation. Erduran and Kutija (2003) proposed a quasi-three-dimensional hydraulic model to investigate the flow characteristics across vegetated surface. Several other studies were conducted on the hydraulic resistance of flexible vegetation (Kouwen and Unny 1973; Järvelä 2002; Carollo et al. 2005; Wilson 2007) but a few analytical velocity distribution model of open channel flow with flexible vegetation exist. Yang and Choi (2010) applied a two layer approach for open channel flow with submerged vegetation where the velocity profile was anticipated to be uniform in the vegetation layer with a logarithmic velocity profile for the upper layer. In recent years, flexible aquatic vegetation, which typically covers a large proportion of a river, has received considerable attention due to its impact on flow and coastal ecosystems (Fonseca and Fisher 1986; Wilson et al. 2003; Järvelä 2005; Sukhodolov 2005; Boller and Carrington 2006). Contrary to the rigid vegetation, flexible vegetation bends under the influence of flowing water. The degree of bending of vegetation varies with the flow velocity, hence a varying degree of flow resistance occurs with the extent of vegetation bending. Hence, the characteristics of open channel flow with submerged flexible vegetation are more complex than that of rigid vegetation. Huai et al. (2013) also applied two-layer model to predict the vertical velocity profile in open channel flow with submerged flexible vegetation. He applied Chen's (2010) theory to estimate the deflection of flexible vegetation submerged in flowing water, and gave an analytical solution for the vertical distribution of stream-wise velocity. The vegetation in channels alters the flow structures, and increases bed roughness, which, in turn, gives a relatively lower flow velocity with consequential impact on the transport of sediment and solute. The dense vegetation are also used for the protection of channel side slopes but roughness coefficients for them are yet to be established fully, which vary with flow characteristics in channels. Although there are unfavorable effects of vegetation on rivers or channels as they reduce conveyance capacity and increase river resistance, but they enhance geomorphic stability and diminish the erosion hazard (Rhee et al., 2008; Tanaka and Yagisawa, 2010; Tsujimoto, 1999).

Further, it has been established that vegetated area such as in channels and wetlands are useful to entrap suspended sediments in the flow (Huang et al., 2008; Jang and Shimizu, 2007). Cotton et al. (2006), Tsujimoto and Shimizu (1994), and Zong and Nepf (2010) have shown that vegetation retains up to 80% of the sediment in transit along downstream in the channels. The extent of trapping suspended load was found to depend on the flow characteristics and vegetation characteristics such as size, shape, flexibility, concentration, and density (Fu-sheng 2008; Jarvela 2005; Sharpe and James 2007; and Wang and Zhu, 2006). In shallow waterways emergent vegetation is also observed to have a significant effect on sediment transport (Leonard and Reed, 2002). Field studies showed that emergent vegetation decreases suspended solid concentrations (Braskerud, 2001; Leonard and Reed, 2002), either by increasing sediment deposition rates or by directly trapping them on stems and leaves (Saiers et al., 2003; Palmer et al., 2004; Huang et al., 2008; Kothyari et al., 2009). Thus, the presence of vegetation removes the suspended solids due to reduction of transport capacity (Elliott, 2000). Yahyapour et al. (2013) conducted experimental investigations to assess the effectiveness of emergent vegetation in an open channel for the removal of Total Suspended Solids and turbidity. They applied response surface methodology to optimize the three variables- flow velocity at the entrance, density of vegetation, and the length of vegetation zone in the vegetated channel. Although the vegetation in channels offers some advantages but its significant retention capacity make them a unwanted for application in channels.

Pagliara and Chiavaccini (2006) used rock chutes as grade stabilization structures in river restoration work. They defined rock chutes as steep and short rough channels having relatively large bed slopes from 0.04 to 0.30 along which the flow is subjected to a greater energy dissipation than in traditional chutes (Pagliara and Peruginelli 2000; Pagliara and Dazzini 2002). They placed boulders with different configurations such as randomly or in rows and found that their presence affects the geometry of the channel and modifies the hydraulic resistance as well. They also attempted to define a relationship between the flow resistance, in terms of both Darcy–Weisbach friction factor and Manning's coefficient, and slope, relative submergence, and rock blocks disposition. Flow resistance of steep riprap placed in constructed channels has also been investigated by Abt et al.(1988) and Rice et al.(1998). The effect of the presence of large scale roughness on flow resistance was also investigated by several researchers (Morris 1959; Peterson and Mohanty 1960; Sayre and Albertson 1961; Mirajgaoker and Charlu 1963; Herbich and Shulits 1964; Rouse 1965; Bayazit 1975; Pyle and Novak 1981; Baiamonte and Ferro 1997; Lawrence 1997, 2000; Ferro 1999; Chanson 2004). These studies clearly revealed that the presence of large scale roughness significantly affect the hydraulic resistance in a channel, hence the flow rate the channels. Meile et al. (2011) conducted experimental investigations in a channel whose banks were riveted with large-scale rectangular roughness elements to assess the flow resistance due to macro roughness of banks. His experiments performed in forty different geometrical configurations revealed that various two-dimensional flow structures in the bank cavities develop by the large scale roughness. He observed that the flow resistance is significantly increased in the macro-rough configuration channels. He also observed that such morphological rehabilitation measures also help in reducing the surge wave-induced rapid water level fluctuations. The propagation and attenuation of the surge waves were also found to be influenced by the channel slope and its roughness (Favre 1935). Since the large-scale bank roughness increased the flow retention capacity of the channel, therefore, they attenuate surge waves attributable to hydro peaking (Stranner 1996). Thus, the large scale bank roughness increases the time of travel but it offers a desirable feature for attenuation of surge waves. An important and general finding of the various studies on macro rough flow resistance is the fact that high roughness density does not automatically mean high flow resistance and particular arrangements of roughness elements can lead to maximum flow resistance. This has been confirmed by the studies on boulders and pebbles (Canovaro and Solari 2006; Pagliara and Chiavaccini 2006a, 2006b) or even for numerical simulations of artificially roughened bed (Stoesser et al. 2004). Therefore, riprap revetment can be a preferred option with low cost.

2.4 Objectives and Methods of Optimal Design

The problem of optimal design of canals caught significant attention of researchers in the past and it has yet sufficient scope for improvement. Guo and Hughes (1984) applied methods from calculus to determine a trapezoidal cross section channel that had minimum hydraulic resistance or channel cost. They provided graphical solution considering freeboard in design problem. Trout (1982) designed trapezoidal, rectangular, and triangular channel sections involving minimum lining costs with composite roughness. Swamee (1995) determined optimal design and section-shape coefficients for circular and parabolic canal sections for minimum seepage-loss canals. He found that the minimum seepage section became very wide and shallow as the canal bed approached the drainage layer. Applying Lagrange multipliers, Froehlich (2008) gave a most hydraulically efficient trapezoidal shape that reduced to two standard sections with rounded bottom vertices used in India, as well as to the commonly used trapezoidal section with sharp bottom vertices. His solutions for the generalized trapezoidal section were shown to match with those of sharp-cornered trapezoids, rectangles, triangles, and semicircles in limiting cases. Froehlich (2011a) further minimized cross-section area to get most hydraulically efficient trapezoidal and triangular drainage channels (that is, those with the smallest possible cross-section areas) whose banks were lined with loose riprap stones. He stated that the drainage channels that convey desired flow rates with the smallest cross-section areas keep excavation costs low, and are the best designs from the hydraulic efficiency perspective (Chow 1959, pp. 160–164; Stephenson 1981, pp. 202–204; Brater et al. 1996, pp. 7-12 to 7-13).

Best hydraulic cross sections of non-erodible channels for several conventional geometric shapes were given by Swamee and Bhatia (1972), Guo and Hughes (1984), Loganathan (1991), Monadjemi (1994), Froehlich (1994, 2008), Swamee (1995), Swamee et al. (2000b), Das (2000, 2007a, 2007b, 2008), Chahar (2005, 2007), Aksoy and Altan-Sakarya (2006), Chahar and Basu (2009), Fox and McDonald 1992, pp. 512–514). Swamee and Bhatia (1972) developed curves for the optimal design of trapezoidal, rounded bottom and rounded corner sections. Guo and Hughes (1984) found that a channel narrower than the hydraulically best section results in minimum excavation when free board is taken into consideration. Monadjemi (1994) and Swamee

(1995) carried out investigations for various canal shapes. Canal cost and practical requirements are normally considered as objective function and constraints (Trout, 1982; Flynn and Marimno, 1987; Loganathan, 1991; Imam et al., 1991; Froehlich, 1994), respectively. Minimum cost design of lined canals involves minimization of the excavation and lining costs subject to uniform flow condition in the canal. A rigid boundary canal is designed for uniform flow formula considering hydraulic efficiency, practicability, and economy (Streeter, 1945). Blackler and Guo (2009) investigated to decide if a channel should be designed for the highest hydraulic efficiency or the least cost. They took construction cost as the sum of the costs for land acquisition, lining material and earth excavation, and found that the differences between the least-cost and most efficient cross sections are closely related to the channel lining to land acquisition cost ratio. They observed that the difference between the two cross sections diminished when the lining to land unit cost ratio vanished. Their analysis revealed that the minimum cost channels tend to become deeper if the land cost is higher than the lining cost. They also stated that the channel construction cost mainly includes costs of land acquisition, lining and earth excavation, and found that the cost of the most hydraulically efficient section can be related to the channel width to flow depth ratio. They expressed that both the most hydraulically efficient section and the minimum cost channel can be formulated and optimized in terms of the channel width to depth ratio. They found the minimum-cost solution sensitive to the trade-off between lining and land acquisition costs. They further observed the minimum-cost channel narrower than the most efficient section, and the difference between them diminished when the lining cost was 20 times or more than the land cost. They mentioned that the two cross sections become identical as the land cost vanishes.

Reddy and Adarsh (2010) applied Genetic Algorithms and Particle Swarm Optimization for the minimum cost design of composite channels that satisfied the specified probability of the channel capacity being greater than the design flow. Different techniques such as Lagrange's undetermined multiplier (Froehlich 1994; Das 2000), sequential quadratic programming (Bhattacharjya 2006), projected augmented Lagrangian multiplier (Das 2007, 2008), Genetic Algorithms (Jain et al. 2004), and non-dominated sorting genetic algorithm technique (Bhattacharjya and Satish 2008) etc. have been used by several researchers. Uncertainty aspect has also been incorporated in the design of open channels such as the hydraulic uncertainty associated with flood levee capacity (Lee and Mays 1986), risk analysis (Tung and Mays 1980; Chow et al. 1988), probabilistic and reliability (Easa 1992, 1994; Das 2007, 2008; and Bhattacharjya and Satish 2008). Bhattacharjya and Satish (2007) incorporated the criteria of side slope stability in the design of an optimal open channel. Das (2007) designed trapezoidal open channels for the minimum cost and the flooding probabilities. He applied the first order analysis for the flooding probability constraint. Das (2008) proposed a chance constrained optimal design model for trapezoidal channels that accounted uncertainties of design parameters. A chance-constrained design considers an open channel whose capacity exceeds the design flow rate with a specified exceedence probability (Easa 1992). The exact analysis, point-estimate methods and the first order second-moment methods are primarily applied to develop the chance-constrained models. The exact method applies numerical integration (Evans 1967, 1972; Hahn and Shapiro 1967) and Monte Carlo simulation (Rubinstein 1981). It involves a comprehensive analysis of the probability distributions of all variables when the reliability level of a system is of critical importance. Das (2010) further investigated the efficacy of the channels having horizontal bottom and parabolic sides as substitute for trapezoidal channels. He adopted minimization of cost and flooding probability as objective function. Salama and Bakry (1992) considered the design of earthen vegetated open channels. Aydogdu and Akin (2011) applied bees algorithm (Pham et al. 2005) for the optimum design of open channels. Using hybrid optimization techniques, Bhattacharjya and Satish (2012) designed a cost effective trapezoidal channel having stable side slopes. Adarsh (2012) presented comprehensive designs of open channels by considering the seepage and evaporation losses, and land acquisition cost along with the lining and excavation costs. He applied a recently developed meta-heuristic technique called as probabilistic global search Lausanne (Raphael and Smith 2003) and incorporated the uncertainty of design parameters in the optimization model using principles of first order uncertainty analysis. He considered the minimization of cost and the flooding risk as the objective function.

However, several other researchers included the uncertainty issue in the modeling of water resources systems (Quarda and Labadie 2001; Levy and Hall 2005; Lu et al. 2009) and applied first order uncertainty analysis in the past (Ganji et al. 2006; Wu et al. 2010; Ganji and Jowkarshorijeh 2011). Bhattacharjya (2005) presented a design of an optimal trapezoidal channel with composite roughness. He considered the minimization of the cost and incorporated freeboard from the change in specific energy consideration in his design to offer a factor of safety against the water level fluctuation in the channel. Adarsh and Reddy (2013) proposed a three-objective probabilistic optimization model for the design of horizontal bottom and parabolic sides channels under parametric uncertainty. Their objective functions included minimization of cost, maximization of probability of expected channel capacity being greater than the design flow and minimization of the overtopping probability. They applied the principles of first-order uncertainty analysis for handling the uncertainty in parameters of the problem and meta-heuristic particle swarm optimization technique. Bhattacharjya and Satish (2008) determined a cost-effective trapezoidal canal considering the seismic stability of homogeneous canal side slopes. They carried out pseudo-static analysis for evaluation of the seismic stability of the slope. However, Reddy and Adarsh

(2011) also designed an optimal trapezoidal channel by considering the slope-stability aspect and they applied particle swarm optimization method.

2.5 Scope for the Present Study

The extensive review of the available literature reveals the fact that the cross-sectional shape, size and wetted surface characteristic affects the discharge capacity. Depending upon the shape and size, the depth of the channel varies to accommodate the design flow rate. The high water table in underlying soil/ bedrock may pose limit on the magnitude of the depth. In addition, higher depth of flow in open channels also results in higher seepage loss, however, other soil characteristics play major role to quantify the magnitude of the seepage losses. The design of the channels normally proceeds with the pre-assigned shape. The large channel widths and mild side slopes usually result in high costs of right-of-way, whereas, small widths on the other hand, may result in constructional difficulties with higher depth of excavation and related increased cost. The steep side slopes can cause slope stability problems in addition to higher erosion rates in earthen channels. Flexible lining that includes riprap (with or without wire cages), can be a better choice of side slope protection against the erosion in earthen channels. The types of riprap stones possess varying characteristics, and therefore their application requires them to be designed for shape and size both. The shape of the riprap stone also affects its stability on the channel side banks; therefore, the shape parameter needs to be incorporated in the design process which is not available in literature. However, an investigation into the suitability of the different types of riprap stones (angular, subangular, subround, and round) (USBR 1991) with their varying physical characteristics (specific gravity, shape and size) are available for the revetment of the channel side slopes from the cost and performance perspectives. Therefore, it leads to provide a scope of investigation into this aspect of riprap stones. The earthen channel banks are susceptible to the slip failure (Bhattacharjya and Satish 2007), therefore, the side slope of the earthen channels are a crucial factor in design process. Though maximum limit for the channel slopes have been suggested by USBR but they may not result in the optimal solution saving cost or improving hydraulic efficiency. Therefore, side slope of the channel is also proposed to be a variable that needs to be determined. A summary of the gaps in the knowledge base on optimal design of earthen channels are:

1. The design of an earthen channel for the minimum cost involving different types of the riprap stones on side slopes with canal bottom unlined is not available in literature, hence this problem is worthy of investigation (Froehlich 2012). Investigations into this aspect of the riprap stones for the minimum cost design of an earthen channel whose side slopes are lined with loose riprap and bottom is unlined is not yet available in the literature. Thus, it leaves a room for investigation into the design of an earthen channel incorporating the

shape and size of riprap stones both for consideration of cost and performance optimality.

2. Swamee et al. (2000b) suggested for incorporating the land acquisition cost in optimization process as the canals run through many valuable lands and property areas. The published literature on design of canals, including land acquisition cost, is yet sparse, hence the present study accounts for the same.
3. The literature reveals that research attempts on optimal design of non-symmetric trapezoidal channels whose side slopes are riprap riveted and bottom is unlined are unavailable.
4. The optimal designs of such channels have not yet considered the sediment-laden flow, which eventually affects the flow characteristics and Manning's roughness coefficient of the channels. Therefore, it leads to another scope for investigation. Inclusion of this aspect adds to an additional novelty in the work.
5. The costs of land acquisition along with the freeboard provision are yet scanty, therefore, this aspect provides another scope of investigation for the minimum cost earthen channels having side slopes riveted with riprap stone and bottom unlined.
6. Effect of the different freeboard scenarios, including a fixed magnitude and depth-dependent cases, has not been investigated for the earthen channels having side slopes riveted with riprap stone and bottom unlined.

Therefore, the present investigation was undertaken to fill up the gap available in literature.