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METHODOLOGIES FOR DESIGN, OPERATION AND MAINTENANCE OF IRRIGATION CANALS SUBJECT TO SEDIMENT PROBLEMS APPLICATION TO PAKISTAN

FINAL REPORT

BY ALEXANDRE VABRE

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DESIGN, OPERATION, MAINTENANCE AND SEDIMENTATION IN IRRIGATION CANALS, A JOINT RESEARCH PROJECT BETWEEN ISRIP(4), IIMI(5) AND CEMAGREF(6)

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FOREWORD

This report is the thesis or final report for the Master of Science program of Mr. Alexandre Vabre. He completed the requirements for an M.S. degree in Environmental Physics and Chemistry from the Nationale Polytechnic Institute of Toulouse, France during September 1996. He spent three months in Pakistan during 1995 and another three months in 1996 to complete all of the necessary field work and analysis. This reproduction is identical with the document accepted by the Nationale Polytechnic Institute of Toulouse.

We have a number of national and international students participating in the research program of the Pakistan National Program of the International Irrigation Management Institute. Their theses and dissertations are retained in our library for ready reference. Only a few of these documents are selected for publication in our research report series. The principal criteria for publishing is good quality research and a topic that would be of interest to many of our national partners.

This report is an output of a collaborative research program with the International Sedimentation Research Institute, Pakistan (ISRIP) and CEMAGREF, the French national research organization for agriculture, water and forests. This research program on sediment transport was formulated in December 1994 and initiated during 1995. This is one of our first reports on sediment transport.

This investigation studied the role of sediment transport in the design, operation and maintenance of irrigation canals in Pakistan. Various numerical simulations have been explored to develop methodologies for design, operation and maintenance of canals having sediment problems. These methodologies have been applied to Chashma Right Bank Canal in Pakistan.

Mr. Alexandre Vabre will begin a Ph.D in December 1996 that is being funded by the French Government and IIMI. The field research will be done on Jamrao Canal in the Province of Sindh. He will be investigating sediment transport through the canal, branch canal, distributaries, minors and watercourses.

Gaylord V. Skogerboe, Director
Pakistan National Program
International Irrigation Management Institute

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I would like to express my gratitude to IIMI staff for their welcome and support during this training period, especially to my supervisor in Pakistan, Prof. Gaylord V. Skogerboe, for his advices and sustain during the work. I remain grateful to Marcel Kuper who has been the precursor of the study and my collaboration with IIMI.

Thus, I would like to express my regards to Cemagref staff for their sustain, especially to my supervisor in France, Dr. Pascal Kosuth, for his involvement and support during the work.

SUMMARY

A first part of the work consists in studying and understanding practices for design, operation and maintenance of irrigation canals in Pakistan. The present large scale irrigation systems in Pakistan are the result of the pioneering work of the British. Design rules still applied and used nowadays were developed by the British engineers from the beginning of the construction of canals. Because of the huge amount of sediments carried by the Himalayan rivers, sedimentation problems appeared very quickly within canals, engineers so tried to include the sediment control in their design rules. To carry out this work, they observed canals that have remained stable during long periods and elaborated correlations between the geometric and hydraulic parameters on the selected canals through the regime method. This an empirical method that imposes regime values for the geometric and hydraulic parameters of the canal in order to avoid sedimentation or scouring phenomenons. To meet these regime conditions, operations on canals were so imposed to maintain full supply discharges and water surface levels. In some cases, because essentially of shortages of water, these regime flow conditions cannot be respected, sedimentation problems are observed and maintenance works are required in canals, it consists generally in excavating sediments from canals up to topographic and geometric data of design.

But problems occur, because of lack of funding, maintenance works are not carried out and canals are getting filled , decreasing gradually the water transport capacity. It seems to be a necessity to improve practices, as well at design, operation and maintenance levels. It passes through the use of numerical simulation tools that allow a good understanding of the hydraulic and sedimentologic phenomenons within irrigation canals. Such simulation tools were developed and calibrated on canals of Pakistan. For the present work, results of the models are considered as reliable and representative, in trends, of the actual physical phenomenons.

A next part of the work consists in using these simulation tools in order to develop methodologies for design, operation and maintenance of irrigation canals subject to sediment problems. This work has been carried out on schematic cases of irrigation canals, nevertheless topographic, hydrologic and sedimentologic data have been borrowed to an actual case of irrigation canal in Pakistan. This choice has been realised in order to obtain a good understanding of the physical phenomenons without the introduction of errors due to the singularities present on an actual case. These methodologies allow to point out general propositions on design rules (from an initial topography, to determine the equilibrium conditions of the canal), operation modes (the effects of different modes on sedimentation rates of the canal) and maintenance strategies (the way to excavate a given sediment volume and the effects on future sedimentation of the canal).

Then a last part of the work consists in applying the methodologies on an actual case of irrigation canal in Pakistan, this work is focused on design and maintenance aspects. Design to predict, using the calibrated simulation models, the evolution of the topographic and geometric parameters on a long functioning period of the canal and maintenance to face the problem of over sedimentation predicted by the models of the selected canal.

RESUMÉ

Une première partie du travail consiste à étudier et comprendre les pratiques de conception, gestion et maintenance des canaux d'irrigation du Pakistan. Les systèmes d'irrigation à grande échelle présents de nos jours au Pakistan sont les fruits du travail de pionniers des Anglais. Les règles de conception encore utilisées et applquées de nos jours ont été élaborées par les ingénieurs Anglais dès les débuts de la construction des canaux. Du fait des quantités gigantesques de sédiments tranportées par les rivières Hymalayienne, les problèmes de sédimentation apparurent rapidement au sein des canaux, les ingénieurs essayèrent donc d'inclure le contrôle des sédiments à leurs règles de conception. Pour ce faire, ils observèrent des canaux qui étaient restés stables prendant de longues périodes et élaborèrent des corrélations entre les variables géométriques et hydrauliques des canaux sélectionnés au travers de la méthode du régime. C'est une méthode empirique qui impose des valeurs de régime aux variables géométriques et hydrauliques dans le but d'empêcher les phénomènes de sédimentation et d'érosion. Pour satisfaire ces conditions de régime, la gestion des canaux fut donc imposée de maintenir les débits et hauteurs d'eau maximaux. Dans certains cas, en raison essentiellement de pénurie d'eau, ces conditions d'écoulement de régime ne peuvent pas être respectées, des problèmes de sédimentation aparaissent et des travaux de maintenance sur les canaux sont nécessaires, ils consistent en général à curer les sédiments des canaux jusqu'aux données topographique et géométrique de conception.

Mais des problèmes aparaissent, du fait de l'abscence de budgets, les travaux de maintenance ne sont pas réalisés et les canaux se remplissent de sédiments, diminuant graduellement la capacité de transport en eau des canaux. Il semble être une nécessité d'améliorer les pratiques, aussi bien au niveau de la conception, gestion et maintenance. Cela passe par l'utilisation d'outils de simulation numérique qui permettent d'obtenir une bonne compréhension des phénomènes hydraulique et sédimentologique au sein des canaux d'irrigation. De tels outils de simulation ont été développés et calés sur les canaux du Pakistan. Dans le cadre du présent travail, les resultats de ces modèles sont considérés comme fiables et représentatifs, en terme de tendance, des phénomènes physiques réels.

Une partie suivante du travail consiste à utiliser ces outils de simulation pour développer des méthodologies pour la conception, gestion et maintenance de canaux d'irrigation soumis au problèmes de sédiments. Ce travail a été réalisé sur des cas schématiques de canaux d'irrigation, néanmoins les données topographique, hydrologique et sédimentologique sont empruntées à un cas réel de canal d'irrigation au Pakistan. Ce choix a été réalisé dans le but d'obtenir une bonne compréhension des phénomènes physiques sans l'introduction de biais dûs aux singularités présentes sur un cas réel. Ces méthodologies permettent de mettre en avant des propositions générales sur les règles de conception (à partir d'une topographie initiale, déterminer les conditions d'équilibre du canal), modes de gestion (l'effet de différents modes sur les taux de sédimentation du canal) et stratégies de maintenance (le moyen de curer un volume donné de sédiments et les effets sur l'envasement futur du canal).

Puis une dernière partie du travail consiste à appliquer les méthodologies sur un cas réel de canal d'irrigation au Pakistan, ce travail est axé sur les aspects de conception et maintenance. La conception pour prédire, en utilisant les outils de simulation calés, l'évolution des paramètres topographique et géométrique sur une longue période de fonctionnement du canal et la maintenance pour parer à un problème d'envasement excessif prédit par les modèles du canal sélectionné.

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U : water flow velocity in the canal — m/s
U_o : regime water flow velocity in the canal (non-silting / non-scouring conditions of flow) — m/s
H : water depth of the canal — m
B : bed width of the canal — m
I : bed slope of the canal — l
J : water surface slope (hydraulic gradient) — l
S^w : wetted area of the canal section — m^2
P^w : wetted perimeter of the canal section — m
R^w : hydraulic radius of the canal section ($R^w = S^w / P^w$) — m
Q : water discharge in the canal ($Q = U \cdot S^w$) — m^3/s
Q_o : regime water discharge in the canal ($Q_o = U_o \cdot S_o^w$) — m^3/s
f : Lacey silt factor — l
d : ponderal average sediment size of the bed materials — mm
d_{50} : median size of the bed materials — mm
w : sediment settling velocity in still water — m/s
C : sediment concentration — kg/m^3
C_E : equilibrium sediment concentration — kg/m^3
q_E : computed sediment discharge in equilibrium conditions (per unit width) — $kg/(m \cdot s)$
C_E : sediment concentration in equilibrium conditions — kg/m^3
Q_S : sediment discharge — kg/s
q_S : sediment discharge of accumulation in a section (per unit width) — m^2/s
ε_s : sediment longitudinal diffusive coefficient — m^2/s
K : Strickler roughness parameter — $m^{1/3}/s$
n : Manning roughness parameter — $s/m^{1/3}$
P : total hydrostatic pressure — $kg/(m \cdot s^2)$
P_i : water-air interface pressure — $kg/(m \cdot s^2)$
τ_i : water-air interface shear stress — $kg/(m \cdot s^2)$
τ_o : shear stress on the canal bed — $kg/(m \cdot s^2)$
u^* : shear velocity on the canal bed : $\tau_o = \rho \cdot (u^*)^2$ — m/s
$\dot{m}_o$: transversal massic discharge — kg/s
$\dot{M}_o$: transversal massic momentum — $kg \cdot m^2/s$
Z_F : bed level — m
ρ : water density — kg/m^3
γ : kinematic viscosity $(\mu = \rho \cdot \gamma)$ — m^2/s
g : acceleration due to gravity — m/s^2
ρ_s : sediment density — kg/m^3
s : relative sediment density (ρ_s / ρ) — l

1. INTRODUCTION

1.1. IRRIGATION AND PAKISTAN

It is estimated that 17 % of the world's cultivated land is irrigated and this land provides 33 % of the globe's harvest. 72 % of this irrigated land lies in the developing regions and in some of these countries, it provides more than half of the annual food production. While the demand for food continues to grow, poor economic performances and rising costs have significantly reduced financial investment in irrigation. As a result, future contributions are focusing on improving existing systems rather than expanding them.

Pakistan is an agriculture country, this is the most important sector of Pakistan's economy. It employs 54 % of the workforce, contributes 26 % of the Gross Domestic Product (GDP), and accounts for 75 % of the country's foreign exchange earnings. Fertile Indus plain and the Indus river system are a major physical asset of its rapidly growing population, estimated at 140 millions inhabitants nowadays, and which is likely to reach 150 millions inhabitants by the year 2000 with the present rates of growth. 70 % of this population live in rural areas.

Pakistan's land, with a total area of 79.6 million Ha, is divided in 4 provinces : Punjab (20.6 million Ha), North West Frontier Province (10.2 million Ha), Sind (14.1 million Ha) and Baluchistan (34.7 million Ha). This total land is estimated to take advantage of 33.8 million Ha of cultivable areas, [3]. Within these cultivable areas, 20.7 million Ha are effectively cultivated, irrigation being employed on about 80 %, indeed the climate in Pakistan is very arid, over half the country receiving less than 200 mm of rainfall per year. This ranks Pakistan at the third place of irrigated lands in the world with an area of 16.2 millions Ha.

The present large scale irrigation systems in Pakistan are the result of the pioneering work of the British. With annexation of the Punjab in 1849 they gained full control over the Indo-Gangetic plains. They were quick to see the enormous irrigation potential of the area and lost little time starting the construction of the Upper Bari Doab Canal, which was completed in 1859. This initiated the development of a network of irrigation systems that will become the largest integrated irrigation system in the world.

The British colonial government considered (and treated) irrigation as a service that was to be provided by the government. As a consequence, a well-defined policy was required to structure the active involvement of the state in the construction and management of *the service* irrigation. The policy formulated by the British not only set goals for government support of this sector, but it defined the core concept of irrigation. In the case Indian sub-continent, this resulted in a concept where the British administration was to provide a vast area and a numerous population with *enough* water from the available resources, in an equitable manner. Enough water was defined as the *minimum* quantity providing a reasonable protection against the effects of severe drought, thus leading to the situation in which many people were to be served by a small amount of water.

As a consequence of partition of the Indian sub-continent (August 1947), the irrigation system was divided between Pakistan and India, without regard to irrigation boundaries. This started dispute India and Pakistan which was resolved through the good offices of the World Bank resulting in Indus Waters Treaty 1960. The Treaty assigned 3 eastern rivers (Sutlej, Beas and Ravi) with mean annual flow of 40.7 billion cubic meters to India and 3 western (Indus, Jhelum and Chenab) with mean annual flow of 166.2 billion cubic meters to Pakistan. This one has profited of a transition period of 10 years of this sharing, during which India has supplied waters from its rivers, in order to develop basic facilities to feed eastern canals. It has consisted in constructing two major dams (Mangla and Tarbela), followed up by a third one (Chashma), several barrages and inter-river link canals under the Indus Basin Settlement Plan (IBSP).

Economic development of Pakistan rests on improving the growth performance of its agriculture sector. Control of timing and amount of irrigation is critical for crop production. The integrated system of inter-river link canals and barrages, and storage reservoirs (Tarbela, Mangla and Chashma) has provided structural facilities for optimum use of the available water resources. Efficient management of these facilities has made it possible to timely deliver and increase the irrigation water supplies at canal head from 91 billion cubic meters (BCM) in 1950-59 to 125 BCM in post-Tarbela period (37 % of increase). Irrigated areas, which were only 10.9 million Ha in 1960-61, has increased to 15.6 million Ha in 1985-86 and the corresponding production of major crops has gone up from a mere 18.4 million tonnes in 1960-61 to 84.4 million tonnes in 1985-86.

Nowadays, the surface irrigation system is the world's largest contiguous irrigated area. The system comprises ... *the Indus and its major tributaries, 3 storage reservoirs, 19 barrages and headworks, 12 inter link canals, 2 siphons, 43 canal commands and 88600 water courses. The length of canals with diversion capacity of 7318 cubic meters per second or 158600 cusecs, is about 57130 km (35500 miles) and of watercourse and farm channels about 1.6 million km...* (Bandaragoda and Badruddin, 1992).

The Indus Basin has one of the world's most favourable environment for large scale, intensive and highly productive irrigated agriculture. Studies by carried out the International Food Policy Research Institute (IFPRI) have indicated that Pakistan and Thailand are the only two countries in Asia with the potential to export food on a sustainable basis into the 21st century. In contrast to these figures, it is also predicted that Pakistan will have significant shortfalls in its national food and fibre production requirement, 10 % by 2000 and 25 % by 2013, largely due to the inefficient use of the nation's scarce water resources.

1.2. SEDIMENT PROBLEMS

The high load of sediment carried by water, coming from erosion in the upper basin of Indus river (Himalayan), induces severe sediment problems. It is estimated that nearly 350000 acres feet (431.7 million m^3) of suspended sediment enters the Indus river system every year, [1]. The sediment content near Shewan, Sind, in the lower Indus is 150000 acres feet (185.0 million m^3). It is assumed that nearly 200000 acres feet (246.7 million m^3) of sediment per year remains in the system and gets deposited in reservoirs and canal systems, comprising irrigation canal ones.

Nieng Chien and Tai Chung (1991) gave a few examples to illustrate the problem of sediments in the rivers fed by the Himalyan Hills : the average concentration is about 4000 *ppm* (4 kg/m^3) in Ganges River, 3000 *ppm* (3 kg/m^3) in Indus River and 38000 *ppm* (38 kg/m^3) in Yellow river where concentrations greater than 600000 *ppm* (600 kg/m^3) have already been measured.

These problems are met at several levels :

⇒ Cultural areas subject to erosion problems,

⇒ Fluvial morphology where river beds can be very unstables,

⇒ Link canals between Pakistan Rivers (with very high design discharges that induce wide sediment quantities in transit) given necessary for the sustaining and the homogeneity of discharges after the Independence of Pakistan (August 1947) and water sharing problems with India.

⇒ Irrigation canals where sediment charges can be very much higher than transport capacities of the water flow where velocities can be very low.

Problem are particularly severe in irrigation canals. On the one hand water surface levels must be kept constant to deliver water to the different offtakes and on the other hand water discharge regularly decreases along any irrigation canal due to farmer offtaking, both these phenomenons induce low velocities, low sediment transport capacities and then the deposition of sediments. This is a major problem in irrigation canals in Pakistan which is also amplified by the flat topography of the Indus basin system with an average slope of 0.25 per 1000.

Within irrigation networks, there are different ways to decrease sediment problems :

⇒ Minimising sediment incomes in the network, through devices that extract sediments,

⇒ Designing canals in such a way that sediments will be transported through outputs of the network (instead of deposited within it),

⇒ Designing specific structures in order to eliminate sediments within the network, through devices that eject or trap sediments,

⇒ Dredging canals with mechanical techniques following up determined maintenance strategies,

⇒ ...

The last solution is of course the one that should never be used (because of its cost) but is inevitable. Optimal management techniques generally consist in using these solutions at the different levels of the irrigation network : so a combined solution is adopted.

1.3. MANAGEMENT OF IRRIGATION CANALS SUBJECT TO SEDIMENT PROBLEMS

Sediment is a serious problem for Irrigation Engineers. It flows through the canal, deposits within or scours its bed, the main consequence is to decrease the canal capacity to transport water. For about one hundred years Irrigation Engineers have given a valiant and ingenious fight to the forces of nature. Innumerable methods and structures have been attempted, sometimes with considerable success, but still many problems are awaiting solutions.

The design of stable alluvial canals, which could deliver water and its sediment charge and which could be economically naintained, must have engaged the attention of man from the very beginning of irrigation practices. That the problem has continuously pestered mankind is amply borne out by the archaeological finds of the old Egyptian, Mesopotamian, Greek and Roman civilisations. The principles on which the old civilisations built and maintained their irrigation system are not known, although canals built as far back as 5000 years ago, are still in use, in Iraq for instance. The interest in the design of stable channels, or the problems underlying such design has continually grown during the last two hundred and fifty years or so, but the developments. during the past few decades can be considered monumental, in spite of the fact that the final solution to this problem has not been attained, [2], *problems underlying such design* being operation and maintenance (O & M) strategies. Both are the main problems for canal managers.

If the sediment control is now taking into account more frequently in the design of irrigation canals, underlying problems such as operation modes (to prefer for instance a mean water supply along the year than a crop based one) and maintenance strategies (for instance mechanic works : to optimise dredged volumes, their periodicity, localisation, etc.) remain in general without solutions.

At this step, it is possible to point out the main importance of design rules in the conception of an irrigation network. This design is going to control the nature, development and application O & M strategies.

1.4. CASES IN PAKISTAN

In Pakistan, in some cases even minor design mistakes have cost the country considerable amounts of money. In 1887, Lower Chenab Canal taking off from the Chenab River was constructed without a regular headwork. It was opened in May 1887 and the canal got filled by sediments within a few weeks. It was dredged from sediments and restarted, it again silted up within a short period. As a consequence, the construction of a proper headwork (Khanki) has been undertaken in 1890-92.

All canals constructed before Khanki, such as Upper Bari Doab Canal taking out from Ravi River or Sirhind Canal taking out from the Sutlej River, had tremendous sediment troubles.

Even though everyone is now aware of the necessity to undertake measures to control sediment, problems also occurred during recent years.

When constructing Marala Ravi Link Canal, the head regulator could not be properly located and the whole canal got silted up within a few years and could not carry the designed discharge. It cost Pakistan the construction of a new Marala Barrage to feed this canal.

1.5. A RESEARCH PROGRAM ON HYDRAULIC AND SEDIMENTOLOGIC MODELING OF IRRIGATION CANALS

In practice, irrigation networks tend to become complex systems. Their head discharge and sediment load vary with time. Along canals offtake discharges and water levels change depending on operational modes and practices. Some local efforts to exclude sediment from a distributary (secondary canal) will result in increasing the sediment load downstream in the main canal.

Improving overall operation of complex networks subject to sediment problems implies the use of numerical modeling through simulation tools that allow to test different solutions before the project realisation.

Hence the development of simulation tools constitute a strong research issue that will allow the elaboration of design, operation and maintenance rules for canals subject to sediment problems.

The work presented in this report was led in the framework of a collaboration project between three complementary research institutes : ISRIP*, IIMI** and Cemagref*** (see presentation Appendix 1,2 and 3)

⇒ **ISRIP*** is devoted to the monitoring and analysis of sediment related problems in irrigation canals of Pakistan.

⇒ * works on the overall management of irrigation networks with a special focus on operation modes applied on irrigation canals,

⇒ **Cemagref***** has developed skills in numerical modeling and simulation of hydraulic systems with a special focus on irrigation canals.

These research institutes are currently joining their efforts to implement a research program that follows up three objectives :

⇒ Improve the knowledge on irrigation canals subject to sediment problems,

⇒ Develop a simulation tool for hydraulic and sedimentologic behaviour in irrigation canals,

⇒ Apply simulation tools to develop methodologies to evolve : **design** (monitoring and diagnosis of sedimentation trends in irrigation canals :real sediment transport capacity, conditions for no-deposition no-erosion), **operation** (analysing the relation between canal operation modes and siltation rate) and **maintenance** (analysing the impact of maintenance strategies on the hydraulic efficiency of a canal) rules.

1.6. APPROACH OF THE PRESENT WORK

1.6.1. OBJECTIVES AND SCIENTIFIC APPROACH

The objective of the training period is the elaboration of methodologies for design, operation and maintenance of canals subject to sediment deposition, using simulation models.

Important note : These methodologies will be developed considering the simulation model of sediment transport SEDI as reliable (calibrated and validated), which means that its results are supposed representative of the sediment transport dynamic in the canals. This hypothesis is of course a simplification and it can induce important errors in results or proposed solutions. Nevertheless it should allow the elaboration of general methodologies that can be applied with progressively improved versions of sediment models like SEDI.

The scientific approach will consist in simulating the sedimentologic evolution of irrigation canals, testing and quantifying the impact of design, operation and maintenance modes and deducing optimised methodologies.

1.6.2. WORK METHODOLOGY

The work methodology can be indented in several steps as below :

⇒ Literature review.

⇒ Diagnosis of the problematic of irrigation canals subject to sediment problems in Pakistan.

⇒ Work on the simulation model : calibration and validation of SIC and SEDI on the case studies.

⇒ Development of methodologies to improve design, operation and maintenance strategies on irrigation canals subject to sediment problems : work on schematic cases of irrigation canals.

⇒ Elaboration synthetical presentations of the methodologies.

⇒ Application of some of the methodological propositions on an actual case of irrigation canal selected in Pakistan.

1.6.3. EXPECTED RESULTS

The expected outputs of this work are :

⇒ To obtain a good assessment of the sediment behaviour in irrigation canals through numerical models,

⇒ To obtain methodological propositions for the elaboration of strategies on design, operation and maintenance of irrigation canals subject to sediment problems.

*** ISRIP : International Sedimentation Research Institute, Pakistan, Lahore, Pakistan.**

**** IIMI : International Irrigation Management Institute, Lahore , Pakistan.**

***** Cemagref : Agricultural and Environmental Research Engineering Institute, Montpellier, France.**

2. LITERATURE REVIEW ON DESIGN, OPERATION AND MAINTENANCE IN PAKISTAN

This work of literature review of the practices in Pakistan should allow to obtain a better understanding on design, operation and maintenance strategies in order to evolve methodologies to improve the practices for irrigation canals subject to sediment problems. It is then indented in three parts : design (see *2.1.*), operation (see *2.2.*) and maintenance (see *2.3.*) of irrigation canals in Pakistan.

2.1. DESIGN OF IRRIGATION CANALS IN PAKISTAN

Whereas water may be released from a storage reservoir to the extent and at the time required by the demand the irrigation system, it is also required that water shall be used when it is available in the river, and is limited to the supply available at the time. This fundamental difference in the nature of the available supply must affect the crops grown and in fact, does also affect the design of the canals.

Clearly the first problem in the design of a project is to reconcile the twin limitations of available supply and area to be irrigated. In connection with supply, it is necessary to know the minimum and normal supplies in the river all along years.

For the area to be irrigated, accurate topographical and contoured surveys are essential : also soil surveys, subsoil water table maps, together with data on rainfall and climate. The statistical records of the irrigation system provide preliminary data as to the amount of water required in the different seasons for the successful irrigation crops.

Detailed design starts at the field with a determination of the water allowance and minimum levels at which this water must be delivered at the outlet. To meet these requirements the process of design, [5], is then indented in the different steps presented below.

The problem of the design of stable alluvial canals (section parameters and slope) has been the subject of wide research works since the beginning of the century and follows up nowadays to be explored by different institutes.

Independently of the ground topography, an alluvial canal can adjust its bed width, its water depth and its slope to reach stability conditions in which it can transport a certain quantity of water and its sediments. This evolution is function of the fluid, its sediments and alluvial periphery, the system so presents three components in its spontaneous evolution, the problem being to determine the behaviour laws of these quantities.

The two main concepts for the resolution of the stated problem are the *regime method* (see *2.2.1.*) which was basically developed in the plains of Indus and Ganges and the *rational method* (see *2.2.2.*) which was developed in Europe and America. Both of these are still under development and represent two extremes methods, it seems judicious in a design project to use a conjunction of these.

The first approach (*regime method*) considers the three components (the fluid, its sediments and alluvial periphery) as a single whole while the second one (*rational method*) assesses the independent dynamics through behaviour laws.

2.1.1. THE REGIME METHOD

The first definition of the *regime method* was given by E.S. Lindley (1919), [7], ...*when an artificial channel is used to convey silty water, both bed and banks scour or fill, changing depth, gradient, and width, until a state of balance is attained at which the channel is said to be in regime. These regime dimensions depend on discharge, quantity and nature of the bed and of berm silt, and rugosity of the silted section; rugosity is also affected velocity, which determines the size of wavelets into which the silted bed is thrown...*

The *regime method* is empirical and states on the observation of the topographic, hydraulic and sedimentologic parameters for a canal that has remained stable during a long period (about 20-30 years). It states relationships, based on correlations, between the average topographic, hydraulic and sedimentologic parameters in order to formulate global equilibrium or regime criterias. The of this method was R.G. Kennedy (1883), executive engineer (XEN) in the Punjab Irrigation Branch (PIB).

The main limitation of these formulas is to state a relationship between average parameters. Indeed, the variability of these parameters during years is not taking into account, this problem may be disturbing in the case of the prediction of canal boundary evolutions. This approach is available only if the actual hydraulic and sedimentologic parameters are constant during prediction periods as well as comprised in thin ranges, the calibration ones. In general, both of these conditions are not respected and the parameters are over estimated in order to enlarge canals, then with a deposition tendency for their future evolutions.

The *regime method*, by its simple formulations, remains mainly used in Pakistan for the design of stable irrigation canals and has been the purpose of wide research works, here follows a summary of the main evolution steps in Pakistan, based on [4], [5] and [6].

In 1934 the Central Board of Irrigation (CBI), Pakistan, adopted Lacey's laws as the basis for designing silt stable alluvial canals. In the absence of a complete *rational method* (see *2.7.2.*), it is recommended, [4], to use Lacey's laws to design unlined (earthen) and lined (either concrete or brick) canals. In the case of lined canals other laws and criteria can be employed for the cross section design but with regard to a Lacey criteria : for instance the regime water flow velocity U_n.

G. Lacey (1928), executive engineer (XEN) in the Punjab Irrigation Branch (PIB), has worked on the regime concept stated by Lindley and has worked on Kennedy and Lindley observed data.

2.1.1.1. Statement of Lacey developments : Generic formula

He has worked on correlations between hydraulic and sedimentologic parameters and has developed a relationship between the regime water flow velocity U_n, the regime hydraulic radius R_n'' (preferred by the author to the regime water depth H_n) and a sedimentologic parameter f (dimensionless), called Lacey silt factor :

$\boxed{U_n = U_n\left(f, R_n''\right) = 0.64 \cdot \sqrt{f \cdot R_n''}}$ (International System Units). (1)

2.1.1.2. Second formula of Lacey

Stimulated by the result of his substitution of the water depth H by the hydraulic radius R'', Lacey proceeded to test the Lindley hypothesis. He has obtained a relationship between the regime wetted area S_n'', the Lacey silt factor f and the regime water flow velocity U_n :

$\boxed{S_n'' \cdot f^2 = 143.05 \cdot U_n^5}$ (International System Units). (2)

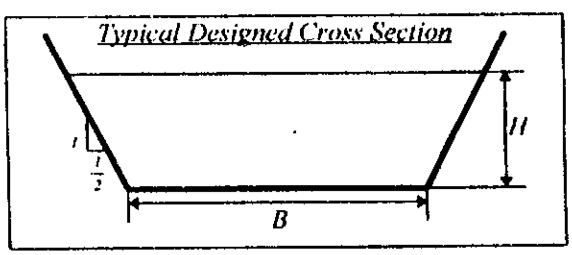
2.1.1.3. Third formula of Lacey

By a simple elimination of the regime water flow velocity U_n in the previous formulas : (1) and (2), Lacey has obtained a relationship between the regime wetted perimeter P_n'' ($P_n'' = S_n'' / R_n''$) and the regime water discharge Q_n ($Q_n = U_n \cdot S_n''$) :

$\boxed{P_n'' = 4.87 \cdot Q_n''^{1/2}}$ (International System Units).

2.1.1.4. Cross section shape about Lacey assumptions

The cross section is chosen by Lacey as trapezoidal with an horizontal bed and a side slope of 1/2 : 1.
This section is the most common use in the construction of irrigation canals during this period and has not been a research subject for Lacey.



2.1.1.5. LACEY'S ABACUS

In order to allow a practical use of his method Lacey plotted abacus as below :

⇒ ***First diagram (see Figure 1) : Q_n (4 to 100 ft^3/s , 0.11 to 2.83 m^3/s), B_n (1 to 30 ft, 0.30 to 9.14 m), H_n (0.5 to 5 ft, 0.15 to 1.52 m) and f (0.4 to 1.6) :***
From a design discharge and a known Lacey silt factor (in general obtained by the observation of other canals of the area), it is possible to determine the canal section parameters : regime bed bottom width B_0 and regime water depth H_0.

⇒ ***Second diagram (see Figure 2) : Q_n (100 to 20000 ft^3/s , 2.83 to 566.34 m^3/s), B_n (15 to 500 ft, 4.57 to 152.40 m), H_n (2 to 20 ft, 0.61 to 6.10 m) and f (0.4 to 1.6) :***
From a design discharge and a known Lacey silt factor (in general obtained by the observation of other canals of the area), it is possible to determine the canal section parameters : regime bed bottom width B_0 and regime water depth H_0.

⇒ ***Third diagram (see Figure 3): Q_n (4 to 20000 ft^3/s , 0.11 to 566.34 m^3/s), I_n (0.01 per 1000 to 1 per 1000) and f (0.4 to 1.6) :***
From a design discharge and a known Lacey silt factor (in general obtained by the observation of other canals of the area), it is possible to determine the regime bed slope I_0 of the canal.

2.1.1.6. LACEY SILT FACTOR FORMULA : $f_s = f(d)$

The Lacey silt factor depends on the ponderal average sediment size d of the particles composing the canal bed, it is equal to 1 where it has been fitted (Lower Bari Doab Canal) and is expressed function of the ponderal average sediment size $d(mm)$ by : $\boxed{f_s = f(d) = 1.76 \cdot \sqrt{d}}$.

2.1.1.7. LACEY'S FORMULAS LIMITATION

Dr. Mushtaq, Irrigation Research Institute (IRI), Punjab, has been the first one to try to determine the sediment transport capacity of canals designed by the *regime method* carrying hydraulic and sedimentologic flows (1961-62). The main conclusion of his works was to establish a rough value for the sediment concentration capacity of a canal designed by Lacey's formulas. Based on his observations, the maximum concentration that can transport such a canal is assessed at *500 ppm* ($0.5\ kg/m^3$).

2.1.2. THE RATIONAL METHOD

The *rational method* consists in solving the specific equations of physical phenomenons like hydraulic, resistance to flow, sediment transport or stability of canal boundaries. This approach may be validated only if physical phenomenons are properly identified and the adapted equations to quantify these phenomenons are chosen. This method, because of lack of validation, has never been employed in Pakistan for the design of unlined earthen canals which are the main in use.

Nevertheless, a recent irrigation project (Chashma Right Bank Canal, NWFP / Punjab), has employed a conjunction of both *regime* (see *2.1.1.*) *and rational methods* for the design of lined concrete portions. The *regime method* has allowed to determine a regime velocity for the water flow (i.e. a velocity such as neither erosion nor deposition occur in the canal, through Lacey's theory) and the *rational method* has allowed to determine the section shape of the canal in order to respect this regime water flow velocity. In the same irrigation project, under the influence of foreign consultants, recent distributaries have been designed using the *rational method* through the *tractive force method*, developed by DuBoys (1879) and follows by host of researchers (no details are provided concerning this method).

Two recent studies, in 1986 and 1992, were carried out to introduce the *rational method* in the design criterias of stable alluvial canals in Pakistan (no details are provided).

2.2. OPERATION ON IRRIGATION CANALS IN PAKISTAN

2.2.1. DEFINITION

A manual, [10], provides the next definition : *Operations are those actions taken to ensure performance of the irrigation system in accordance with the instructions for use spelled out by the designer in agreement with the developer, so that the objectives of the project can be fully attained. The operation function also incorporates : provision of technical support and other related advisory services for system users; exercise of responsibility for balanced management to ensure sustainability; and collection of user fees. Finally, it is part of the operation function to ensure compliance with both statutory regulations and system rules governing users. In other words, administration of water stocks and policing of water regulations are included.*

The next presentations are based on [10] and [11].

2.2.2. PROBLEM STATEMENT

Before the independence of Pakistan, distribution of available river supplies in the canal system was made on the basis of historic rights or sanctioned allocations determined as a result of the findings of various committees / commissions appointed by the then Government of India. As a result of construction of Indus basin works, the canal system in Pakistan has been grouped into following two zones, the Jhelum-Chenab and Indus ones.

Canals in the Jhelum-Chenab zone receive their supplies from Mangla reservoir, Jhelum and Chenab rivers, through a network of inter-river link canals. These canal systems command 5.3 *million Ha*, they cannot be fed, because of their location, from the Indus. All these canals are located in the Province of Punjab. Thus the waters of Mangla reservoir as well as the flows of the rivers Jhelum and Chenab are not shared.

Canals of the Indus zone command 8.7 *million Ha* and are located in all the provinces of Pakistan. Water supplies of the Indus zone are shared by all the four provinces.

Pending the final decision on water apportionment among the provinces, adequate arrangement are being followed for sharing the waters of the Indus river and its storages. In 1977-79 the Water Distribution Committee (WDC) was appointed for the allocation and distribution of Indus waters till such time that water apportionment is decided. The committee meets as required to decide the provincial allocation on a seasonal basis (*rabi* season, autumn / winter, and *kharif* season, spring / summer).

The typical arrangement made for the distribution of waters of the Indus river to the provinces is to deduct the requirements NWFP and Baluchistan provinces. The remaining resource is divided between Punjab and Sind provinces in the ratio of 1/3rd and 2/3rd respectively. Because any province should not receive more water than required, Water And Power Development Authority (WAPDA), who regulates the supply, must be notified so that the surplus water may be used by each province.

The reservoirs are filled during *kharif* season. The filling is started when inflow exceeds requirements, it generally starts in June and reservoirs are full at the end of August. The water stored in reservoirs is released in 3 phases : late *kharif* (during September), *rabi* (October to end March) and early *kharif* (April till reservoir filling starts to the beginning of June).

The three on-line reservoirs Tarbela, Mangla and Chashma, and inter-river link canals are structural facilities that play key role in water and load management. As the reservoirs have multipurpose and interprovincial functions responsibility of their operation has been retained by the Federal Government through WAPDA. Operation of the reservoirs is conducted by WAPDA in liaison with different federal and provincial agencies.

2.2.3. WARABANDI OR WATER TURNS

The canals in Pakistan are designed on the *regime method* (see *2.1.1.*). These regime conditions of flow provide the stability of the canal boundaries (neither deposition nor erosion) during a long period of functioning but require that the water discharge within the canal is constant during the year and equal to the design one, they also require that the sediment charge lower than a given value. For Pakistan canals, with the applied design formulas, this value has been assessed at *500 ppm* ($0.5\ kg/m^3$).

Certain canals having been designed before the important shortages of the water resource, the water sharing within canals cannot be regular in time, affecting discharge values. A system of rotations, during given periods, for the water distribution has then been imagined and implemented since a long time and has become traditional in the irrigation practices of Pakistan. It is called *warabandi* and is a rotational method for an equitable distribution of the available water resource in an irrigation network. The term *warabandi* means *turns* (*wahr*) which are *fixed* (*bandi*).

A condition for the good functioning of this water distribution system is the quality of the feeding canal. In order to respect an equity in the distribution, flows in main, branch canals, distributaries and minors have to be steady to be able to deliver the same quantity of water for each turn.

As an integrated water management system, *warabandi* is expected to achieve two main objectives : high efficiency (through the imposition of water scarcity on each and every user) and equity in distribution (through enforced equal share of scarce water per unit area among users).

Different levels (scale and frequency) of *warabandi* exist depending on the application canal : main, branch canals, distributaries, minors and watercourses.

2.3. MAINTENANCE OF IRRIGATION CANALS IN PAKISTAN

2.3.1. DEFINITION

A manual, [10], provides the next definition : *The maintenance is the set of actions which makes it possible to maintain an investment in a given condition, restore it to such condition, or ensure that it is able to continue providing a given service. Thus the purpose of the maintenance is to guarantee the uninterrupted normal functioning of a system so that it can meet its assigned objectives. The maintenance here has a broad meaning, referring to more than the upkeep of separate items of equipment. Thus the concept of maintenance will incorporate not only the upkeep of each of the complex constituent parts of a system, but also the entire set of actions needed to guarantee its uninterrupted functioning, including analysis of incidents and results as a means of identifying improvements needed if system objectives are to be met.*

The next presentations are based on [10], [12], [13] and [14].

2.3.2. PROBLEM STATEMENT

Large volumes of water are conveyed over long distances by canal systems made in general of earthen banks. The material of the banks is the soil available locally. Water levels in the canals are usually much above the country sides, in come cases by several feet. A failure of the bank of a canal, in addition to causing considerable damage to the country side and private property, may ruin the crops grown on that canal system by reason of interruption to supply. The actual damage varies with the size and site of the canal and the material of the bank, but it is clear enough that the efficient maintenance of a canal system is of main importance to the welfare of the province.

Evidently it is essential that the section of a canal shall be maintained always as close to the design conditions as possible. The data actually adopted for each canal is given on the sanctioned longitudinal section of the canal. It is the duty of the sub engineer (SE) and sub divisional officers (SDO) to see that the actual section is not very much below the design cross sections. Whenever they find that the banks are damaged, whether in width or in height, they must submit proposals and estimates to restore the banks to design sections.

The next items of importance is the maintenance of the hydraulic characteristics of the canal. The maintaining of the hydraulic regime conditions of flow (see *2.1.1.*) in the irrigation canals is of great importance. The capacity of a canal to carry its full supply discharge and to provide the full supply water levels depend on an efficient maintenance of its boundary characteristics.

The maintenance of equitable distribution of supplies has next to be considered. This is very important in the case of distributaries where according to the present Punjab practice, the further distribution is automatic with authorised discharge entering a particular canal at its head, the requisite full supply discharges and water surface levels must reach each outlet from the head to the tail of the canal.

In Pakistan, development of water resources is the responsibility of the Federal Government and Water And Power Development Authority (WAPDA) is responsible for the planning and construction of the storage and headwork facilities and their maintenance.

The repair and maintenance (R&M) of the irrigation system is the responsibility of the Provincial Irrigation Department (PID). The responsibility begins at the diversion point and ends at the outlets, i.e. the watercourse head. Below the outlet, R&M is the responsibility of the water users, i.e. the farmers.

Irrigation canals in Pakistan are designed to be in regime conditions of water and sediment flows (see *2.1.1.*). This choice has been carried out deliberately in order to minimise maintenance costs in irrigation networks.

2.3.3. EXPERIENCE OF DESILTING CANALS

2.3.3.1. PROBLEM STATEMENT

Desilting of canals, before the independence of Pakistan, had been carried out in a well planned manner as part of remodelling canal system. The canals were monitored after the desilting operation and further remedial measures were taken in time to set the canals to their required design parameters and to control the excessive sediment entry into the canal at the head regulator. The main objective of the irrigation engineers was to diagnose the cause of sedimentation problems in the canal by monitoring canals on a continuous basis, remodelling the canal and its hydraulic structure in a proper manner by the application of their skills.

After the independence of Pakistan (August 1947), these good engineering practices continued, the canals were remodelled and their longitudinal sections were observed and revised every five years. As part of these schemes, distributaries or minors were desilted by the Irrigation and Power Department in a well planned manner. With the passage of time, due to a lack of financial control and resources, this practice did not continue. This has resulted in the sedimentation of canals in the head reaches causing :

⇒ Inadequate freeboard in the upper reaches, thereby endangering the safety of canal banks,
⇒ Inadequate distribution of irrigation water within the canal system,
⇒ Shortage of irrigation water to some tertiary or quaternary canal heads (i.e. at the distributary or minor tails),
⇒ ...

2.3.3.2. EFFECT OF DESILTING

The canal behaviour depends on the adoption of canal topographic and geometric parameters. The measures for berm formation, such as killa bushing, may lead to constricting the canal and preventing sedimentation. In this case, the canal would behave as a self bed eroding canal, and subsequently, attains stable conditions. Supportive measures for berm formation and attainment of canal stability has been found successful in exceptionally wider and shallower canals. The main parameter which effects the subsequent behaviour of the desilted canal is the regraded slope. The sediment transport relations developed by scientists and engineers indicate that the slope of the canal has a predominant effect on its sediment transport capacity being a croissant function of the bed slope. In case the canal slope cannot be increased beyond a certain limit due to a command constraint or topographical limitations, the regraded canal may again become silted. Therefore the only remedy to obtain the canal stability lies in the prevention of excessive sediment entry into canals by provision of sediment structures (see *3.2.*) on the canals.

The other parameter which is affected by the desilting of canal is the full supply level within a canal reach. There may occur some deviations in the actual water surface levels, resulting in an inequitable water distribution between the outlets. If the outlets are not adjusted according to the remodelled full supply levels of the canal, it may happen that either the bank freeboard becomes inadequate or flooding of tail reaches takes place. Therefore any desilting operation and regrading of the canal bed requires an adjustment of outlets with regard to :

⇒ An equitable distribution of irrigation water according to the cultivable command area designed capacity of each outlet,

⇒ A crest setting of outlets according to the regraded bed level of the canal so as to draw the proper share of sediment from the canal.

⇒ ...

2.3.3.3. *THE SELF HELP BASIS DESILTING CAMPAIGN OF 1992*

The Punjab Provincial Government started a desilting campaign on a self help basis in the year 1992, this program is still continuing during the annual closure of canals from mid-December to mid-January. The provincial government, being aware of the vital importance of the canal irrigation system, attaches top priority to the efficient working of this system. About 50 to 70 % of the maintenance and repair budgets are allocated for the sediment excavating of distributaries and minors and the regrading through berm cutting of main, branch canals, distributaries and minors. With the passage of time, the Irrigation and Power Department input towards the desilting operation of distributaries and minors has been reduced because of inadequate financial resources, resulting in less budgetary allocation from the provincial governments for this purpose.

For the last many years, farmers started on their own sediment clearance of distributaries and minors on a small scale, in their respective canal command areas on a self help basis. Therefore, for the provincial governments, mobilising the farming community for the desilting of irrigation canals on a self help basis offers an attractive alternative to partly overcome the resource constraints.

This campaign based on a self help basis has been successful in terms of farmers and village population participation in irrigation management. To some extent farmers at the tail end of distributaries or minors have been able to receive their due share of irrigation water supplies. It is felt that with the proper planning of desilting operations by the Irrigation Department, keeping in view its glorious past experience of remodelling schemes, these efforts may prove beneficial in improving the canal behaviour, such as equitable irrigation water supplies to the farmer for a longer duration. There is a need to monitor the canal conditions which have been desilted with regard to its canal geometric parameters, canal full supply and bed levels, the quantity of irrigation water received by the farmers and its effects on crop yields.

3. TRANSITION : PROBLEM STATEMENT

Design, operation and maintenance rules of irrigation canals in Pakistan are mainly empiricals and do not take into account the different aspects presented above such as : variable discharges, variable sediment concentrations, problems of very high sediment charges.

Design rules are based on the *regime method* (see *2.1.1.*), operation modes and maintenance strategies are imposed as a consequence of this design choice. It is very restrictive and imposes regime conditions of water flow, i.e. constant water discharge in canals equal to the design one and sediment concentration lower than a critical value (500 *ppm*, 0.5 kg/m^3). In comparison with charges transiting rivers that feed canals of Pakistan, it appears wide differences between charges within these rivers and the sediment transport capacity of irrigation canals. The Indus river feeds numerous irrigation canals within Pakistan, the average annual concentration is *3000 ppm* (*3* kg/m^3), Nieng Chien and Tai Chung, 1991, thus 6 times bigger than the estimated transport capacity of canals ! Sediment structures are provided in order to decrease the sediment charges entering or within irrigation canals but still problems of sediment occur.

It seems to be a necessity to improve these rules in order to address the sediment problem. It is only possible using numerical tools for the assessment of the topographic, hydraulic and sedimentologic parameter dynamics and to obtain a better understanding of the physical phenomenons. Indeed, these numerical tools allow to determine the effects of variable discharges and sediment concentrations on the topographic parameters by solving the appropriate physical equations.

In the next work, this approach is applied. A part consists of the calibration of numerical tools in order to simulate the water and sediment flows in irrigation canals. Another part of the work consists of the use of these numerical tools as a work basis for the development of methodologies for design, operation and maintenance in irrigation canals subject to irrigation problems, it is realised on schematic cases of irrigation canals, this choice has been done to reduce the most as possible the interpretation errors of the physical phenomenons on an actual case. Nevertheless, topographic, hydrologic and sedimentologic data have been borrowed to an actual case of irrigation canal in Pakistan.

These methodologies will allow to point out general propositions for design, operation and maintenance aspects on irrigation canals subject to sediment problems.

Then a last part of the work consists in applying propositions on an actual case of irrigation canal in Pakistan. This work is focused on design and maintenance aspects, on the one hand the evolution of the canal topography and geometry are studied through the design work, on the other hand the way to maintain a target topography is studied through the maintenance work.

4. HYDRAULIC AND SEDIMENT TRANSPORT : PHENOMENONS AND MODELING

4.1. HYDRAULIC

4.1.1. PHENOMENONS

The next hydraulic resolution concerns gravitational flows in canals, under sub-critical flow conditions. Super-critical passages are nevertheless allowed, for instance at the level of structures, but are not taking into account by the model.

The hydraulic resolution has been chosen in steady regime, or as a succession of steady regimes when the simulated period is too long to be considered as globally steady. The quality and reliability of the results is of a great importance for the follow up of the work concerning the sediment transport modeling, indeed errors introduced in this step could hide some physical phenomenons of the sediment transport.

4.1.2. EQUATIONS

These developments are based on "Hydraulic Lessons", [15].

The generic equations of liquid phase conservation for a gravitational flow (with x the direction of the flow) are :

Mass conservation :

$$\boxed{\frac{\partial}{\partial t}(\rho \cdot S_w)+\frac{\partial}{\partial x}(\rho \cdot U \cdot S_w)=\frac{d}{dx}(\dot{m}_o)} \qquad (1)$$

Momentum conservation :

$$\boxed{\frac{\partial}{\partial t}(\rho \cdot U \cdot S_w)+\frac{\partial}{\partial x}(\rho \cdot U^2 \cdot S_w)=-S \cdot \frac{\partial P}{\partial x}-\tau_o \cdot P_w+\tau_i \cdot B+\rho \cdot g \cdot S_w \cdot \sin(\alpha)+\frac{d}{dx}(\dot{M}_o)} \qquad (2)$$

where : $\tan(\alpha) = I$.

Hypothesis of hydrostatic distribution of pressure :

$$\boxed{\begin{array}{l} P = P_i + \rho \cdot g \cdot \cos(\alpha) \cdot (H - z_r) \quad \text{and then :} \\ -\frac{1}{\rho} \cdot \frac{\partial P}{\partial x} = -\beta \cdot g . \cos(\alpha) \cdot \frac{\partial H}{\partial x} \end{array}} \qquad (3)$$

where β is a corrective coefficient depending on the flow uniformity.

The equation system : (1), (2) and (3), without transversal contributions, i.e. $\dot{m}_o = 0$ and $\dot{M}_o = 0$, is also called ***Saint Venant System of Equations.***

The flow is called ***uniform*** if :

⇒ Cross sections are constant and keep constant parameters (roughness, slope, etc.),

⇒ The flow is parallel to the bottom bed (this implies an hydrostatic distribution of pressure),

⇒ The interface liquid-air is flat and the pressure P_i is constant, $\beta = 1$ (see above), the interfacial shear stress τ_i is negligible,

⇒ The flow is ***steady***, in this case the shear stress on the canal bed is expressed by : $\tau_o = \rho \cdot g \cdot R_H \cdot J$.

In ***uniform flow***, without lateral contributions (i.e. $\dot{m}_o = 0$ and $\dot{M}_o = 0$), equations (1) and (2) permit to express the shear stress on the bed as : $\tau_o = \rho \cdot g \cdot R_H \cdot I$, in this particular flow conditions : $I = J$.

4.1.3. NUMERICAL RESOLUTION

The numerical method of resolution can be indented in two types :

⇒ ***Steady flow*** : resolution of the integral water surface level equation, through a ***Gauss scheme***,

⇒ ***Unsteady flow*** : resolution of the ***Saint Venant System of Equations***. This system being not analytically solved on an actual geometry, a numerical resolution is used by discretising equations, i.e. the partial derivatives are substituted by finite differences, through a ***semi-implicit Preissman scheme***. This is an implicit scheme because, in the spatial derivative formulations, physical parameters are expressed for unknown time steps.

4.1.4. SIC SOFTWARE

Presentation based on [17].

The SIC software is a mathematical model which can simulate the hydraulic behaviour of most of the irrigation canals, under steady and unsteady flow conditions. The main purposes of the model are:

⇒ To provide a research tool to gain an in-depth knowledge of the hydraulic behaviour of the main canal.
⇒ To identify, through the model, appropriate operational practices at regulating structures with a view to improving the present canal operations.
⇒ To evaluate the influence of possible modifications to some design parameters with a view to improving and maintaining the capacity of the canal to satisfy the discharge and water elevation targets.
⇒ To test automatic operational procedures and evaluate their efficiency. (Such procedures will have to be written by advanced model users).

Steady flow computations can be performed on any type of hydraulic networks, but unsteady flow computation only on non-looped canal configurations.

The SIC model is an efficient tool that allows the canal manager as well as the researcher to quickly simulate a large number of hydraulic design and management configurations on the canal. The software is menu driven so as to be user-friendly. The user can call upon an on-line help procedure during the calculation.

4.2. SEDIMENT TRANSPORT

4.2.1. PHENOMENONS

These developments are based on "Sediment Transport and River Morphology", [16].

The motion of sediment particle in a water flow can be sepatated in 2 major modes as below :

⇒ ***Suspended load*** indented in two particle natures as below :
- ***settled particles*** in general the same as the bed materials,
- ***non-settled particles*** very fine and coming from the wash of the upstream feeding reservoir, this portion is called ***washload***. It is composed of very fine and cohesive particles, with a median diameter lower than *62.5 microns* (actually *1/16 mm*, it is the lowest size of the mesh when a sediment sample sifting is realised and this value has been chosen as a reference). This load, because of its very small fall velocity, remains transported in the flow. Actually, the reference size of *62.5 microns* is not respected in flows, energy criterias (for instance Yang), depending on hydraulic characteristics, can be used to determine the reference particle size for the washload, it can reach *10 microns*.

⇒ ***Bed load*** indented in different ways of particle motion as below :
- jumping successively on the bed, called saltation,
- rolling on the bed,
- sliding on the bed.

The main phenomenons for the sediment transport in irrigation canals are the transfer of fine sediments in suspension within the water flow. This transfer can be indented in two types :

⇒ ***Equilibrium*** : it appears when the water flow carries a sediment concentration related to its capacity of transport, in this case neither deposition nor erosion occur,
⇒ ***Non-equilibrium*** : it appears when the water flow carries a sediment concentration not related to its capacity of transport. On the one hand, the transported sediment concentration is lower than the transport capacity, erosion may occur (hydraulic stresses must sufficient). On the other hand, the transported sediment

concentration is greater than the transport capacity, deposition occurs. The last case is mainly observed in the follow up of this work concerning irrigation canals in Pakistan.

4.2.2. EQUATIONS

Sediment conservation :

$$\boxed{\frac{\partial}{\partial t}(S_w \cdot C)+\frac{\partial}{\partial x}(Q \cdot C)=q_s+\frac{1}{\rho}\cdot\frac{d}{dx}(\dot{m}_a)\cdot C+\frac{\partial}{\partial x}\left(\varepsilon_s \cdot S_w \cdot \frac{\partial C}{\partial x}\right)} \qquad (1)$$

where :

⇒ The first member is the transport term: inertia and advection of the quantity C within the flow,

⇒ In the second member :

- the first term q_s is the accumulation in a section, either positive (well term of erosion) or negative (source term of deposition), per unit width,
- the second term is lateral contributions,
- the third term is longitudinal diffusion.

The sediment conservation equation (1) has been simplified according to several hypothesis. They consist in neglecting the inertia, lateral contributions and diffusive term, justifications are :

⇒ ***inertia :*** choice of a steady resolution of the sediment transport,

⇒ ***lateral contributions :*** low influence of the lateral contribution in the sediment transport resolution,

⇒ ***diffusive term :*** the longitudinal diffusion term is negligible, second order (it remains also a wide difficulty to model the longitudinal dissipative coefficient ε_s).

So equation (1) becomes :

$$\boxed{\frac{\partial}{\partial x}(Q \cdot C)=q_s} \qquad (2)$$

where advection and accumulation terms remain.

4.2.2.1. EQUILIBRIUM CONDITIONS

The sediment transport is called in ***equilibrium conditions*** when the flow carries a sediment concentration related to its capacity of transport. It implies that the q_s term (accumulation in a section) is nil. In this case there is neither deposition nor erosion.

Equation (2) becomes : $\boxed{\frac{\partial}{\partial x}(Q \cdot C)=0}$

By immediate integration we obtain : $\boxed{(Q \cdot C)_E = cste = q_E}$

The right term of this equation is determined through an empirical sediment formula which expresses an equilibrium sediment discharge q_E (per unit width) function of hydraulic and sedimentologic parameters of flow. Several authors have already stated these type of empirical laws : Einstein, Brown, Karim and Kennedy, Ackers and White, Van Rijn, Engelund and Hansen, etc.

4.2.2.2. NON-EQUILIBRIUM CONDITIONS

The sediment transport is called in ***non-equilibrium conditions*** when the flow carries a sediment concentration non related to its capacity of transport. The q_s term (accumulation in a section) expresses this imbalance.

Depending on cases the sediment concentration is greater (lower) than the transport capacity , there is deposition (either erosion or nothing) and the q_s term is a source (well) one so negative (positive or nil). Indeed in the case of erosion, this phenomenon may appear, hydraulic conditions must be sufficient to allow the initiation to sediment motion.

Equation (2) keeps its generic shape : $\boxed{\frac{\partial}{\partial x}(Q \cdot C) = q_s}$

The right term q_s (accumulation in a section) requires a spatial delay loading law that expresses a relationship between q_s and hydraulic and sedimentologic parameters. Different expressions, following up more or less complex developments, for instance including imbalance, diffusive and various terms, have been stated by several authors: Krone and Parthéniades, Daubert and Lebreton, Han, etc.

4.2.3. *NUMERICAL RESOLUTION*

4.2.3.1. *EQUILIBRIUM CONDITIONS*

The equation of sediment conservation is expressed by : $\boxed{(Q \cdot C)_E = cste = q_E}$

The chosen equilibrium law is the ***Engelund and Hansen*** (1967) one : $\boxed{q_E = \beta \cdot \frac{.U^5}{(s-1)^2 \cdot \sqrt{g} \cdot d_{50} \cdot C_H^3}}$, where

β (dimensionless) is a parameter fitted by experimentation.

The related equilibrium sediment concentration is expressed by : $\boxed{C_E = \rho_S \cdot \frac{B}{Q} \cdot q_E}$.

Calibration and validation of β parameter consist in facing the equilibrium computed concentrations with actual measured ones.

Numerical resolution :
The sediment concentration $C_E(x_i)$ is computed from upstream to downstream for each computed cross section x_i of SIC software.

4.2.3.2. *NON-EQUILIBRIUM CONDITIONS*

The equation of sediment conservation is expressed by : $\boxed{\frac{\partial}{\partial x}(Q \cdot C) = q_s}$

The chosen spatial delay loading law is the Han (1980) one : $\boxed{q_S = K.Q.(C_E - C)}$, where K (m^{-1}) is expressed by $\boxed{K = \alpha \cdot \frac{w}{u}}$ and α (m^{-1}) is a parameter fitted by experimentation.

For the practical implementation of the α parameter it is necessary to separate 2 cases :

⇒ Deposition : $\boxed{\alpha = \alpha_D}$.

→ Erosion : $\boxed{\alpha = \alpha_E}$.

Calibration and verification of α parameter consist in facing computed (predicted) concentrations or bed evolutions with actual measured ones.

Numerical resolution :

The solved equation is : $\boxed{\frac{\partial C}{\partial x} = K \cdot (C_E - C)}$, under the hypothesis of a constant discharge Q.

The analytical solution of this equation, on a segment (x_i, x_{i+1}), is : $\boxed{C(x) = C_E + (C(x_i) - C_E) \cdot e^{-K \cdot (x - x_i)}}$, under the hypothesis :

⇒ K has low variations on the segment (x_i, x_{i+1}) and remains near the average of $K(x_i)$ and $K(x_{i+1})$.

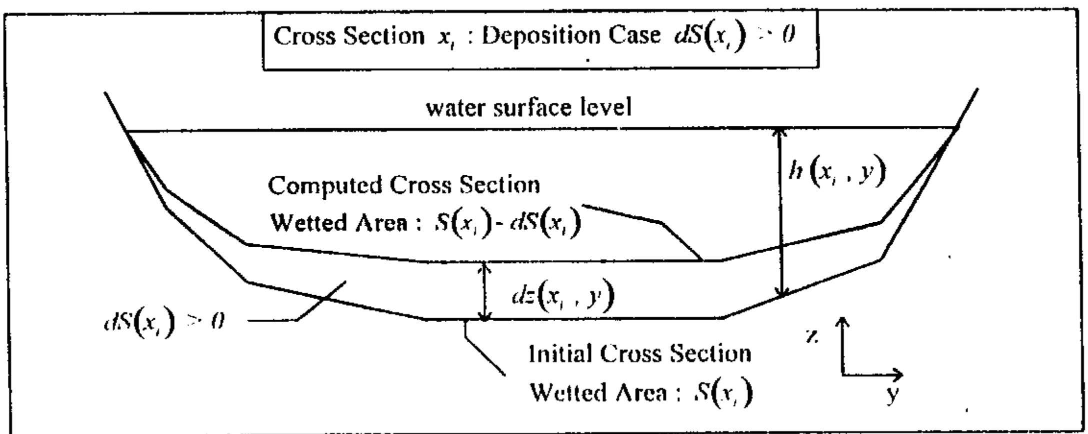
⇒ C_E has low variations on the segment (x_i, x_{i+1}) and remains near the average of $C_E(x_i)$ and $C_E(x_{i+1})$.

Then, knowing the sediment concentration $C(x_0)$ at the head of the canal, the sediment concentration $C(x_i)$ is computed from upstream to downstream for each computed cross section x_i of SIC software.

4.2.3.3. *CROSS SECTION EVOLUTION*

From the knowledge of the sediment concentration along the canal $C(x_i)$, the sediment discharge $Q_s(x_i)$ is known. The term of accumulation of sediments in a cross section x_i is directly deducted from the variation of the sediment discharge $Q_s(x_i)$ along the canal. It allows to express the sediment volume (per unit length) $dS(x_i)$ that deposits in the cross section x_i, for a given duration of the steady flow.

An hypothesis has then to be formulated in order to distribute the area $dS(x_i)$ in the cross section x_i. It has been chosen to share $dS(x_i)$ function of the water depth $h(x_i, y)$, the variation of the bed level $dz(x_i, y)$ is expressed by : $\boxed{dz(x_i, y) = h(x_i, y)\cdot\frac{dS(x_i)}{S(x_i)}}$, see figure below :



Cross section evolution

4.2.4. *SEDI MODULE*

4.2.4.1. *PRESENTATION*

The sediment transport module SEDI is programming in FORTRAN (excepted the command program which is in PASCAL).

The functioning of the module is as below :

⇒ Reading of the geometric file of the studied canal : result of SIC software computation,
⇒ Reading of the hydraulic and sedimentologic data file : data for the next hydraulic and sediment computations,
⇒ Computation of the hydraulic flow : SIC computation,
⇒ Computation of the related sediment flow : SEDI computation,
⇒ Computation of the transformed geometry of the canal : SEDI computation according to the previous results, and writing of a transformed geometric file for the next computation of the hydraulic and sediment flows.

4.2.4.2. *CALIBRATION OF THE MODULE*

For the calibration of the module, two choices are possible depending on the available data and needs of use.

The first one, called *"instantaneous calibration"*, consists in adjusting the parameters of the model : β, α_D and α_E, on actual evolutions of the sediment concentrations along the canal, i.e. each parameter is fitted on periods and portions corresponding to its proper dynamic : equilibrium, deposition or erosion. It remains a wide difficulty to select these periods and portions, nevertheless this calibration method allow to predict the sediment concentration distribution within the canal which is, in particular conditions of use, a necessity.

The second one, called *"integral calibration"*, consists in adjusting in the same time the parameters of the model : β, α_D and α_E, on actual evolutions of the canal topography and geometry for a given period with regards to minimising an error function J under the constraint of the sediment mass conservation, expressed by :

$$\Rightarrow \boxed{J = \sum_{i=1}^{n}\left[\left(dS_{comp}(x_i) - dS_{meas}(x_i)\right)\cdot\left(\frac{x_{i+1} - x_{i-1}}{2}\right)\right]^2},$$

$$\Rightarrow \boxed{\frac{\Delta\ mass}{\rho_s} = \Delta\ Vol = \sum_{i=1}^{n}\left[\left(dS_{comp}(x_i) - dS_{meas}(x_i)\right)\cdot\left(\frac{x_{i+1} - x_{i-1}}{2}\right)\right] = 0}.$$

For the calibration both of these criterias have to be respected. This calibration method requires less data than the previous one, only topographic, geometric and head values of the discharges and sediment concentrations are required, and is interesting for the prediction of topographic and geometric parameters such as bed slope, sediment volumes (deposited or eroded in the canal). This method of calibration has been chosen in the follow up of the work to develop methodologies for design, operation and maintenance because sediment volumes are interesting parameters for this purpose.

5. METHODOLOGIES FOR DESIGN, OPERATION AND MAINTENANCE OF IRRIGATION CANALS

5.1. PRESENTATION

This part deals with generic presentations of methodologies for design, operation and maintenance on an irrigation canal, here are the steps that have to be followed in order to elaborate such methodologies.

5.1.1. METHODOLOGIES OF DESIGN

The methodologies for the design of an irrigation canal can be indented as below :

1. ***Hydraulic and sedimentologic analysis :***
   - ⇒ Topography of the command area : natural ground slope,
   - ⇒ Discharge distribution in the feeding river,
   - ⇒ Sediment concentration distribution in the feeding river,
   - ⇒ Discharge required at the head of the canal,
   - ⇒ Discharges and water surface levels required for the off-takes.
2. ***Sizing of the canal :***
   It consists in sizing the canal following empirical rules for the determination of the section parameters :
   - ⇒ Side slope,
   - ⇒ Bed width,
   - ⇒ Water depth.
3. ***Implementation of the numerical models :***
   - ⇒ Hydraulic model : implementation, calibration and validation,
   - ⇒ Sedimentologic model : implementation, calibration and validation.
4. ***Test by simulation of the sizing :***
   - ⇒ Test by simulation of the behaviour of the canal topographic and geometric parameters during a long period of functioning,
   - ⇒ Correction or validation of the sizing rules.

5.1.2. METHODOLOGIES OF OPERATION AND MAINTENANCE

The methodologies for operation and maintenance on an irrigation canal can be indented as below :

1. ***Analysis of the system :***
   - ⇒ Topography of the command area : natural ground slope,
   - ⇒ Description of the primary canal (main or branch canal), secondary / tertiary canals (distributaries or minors) and tertiary / quaternary canals (watercourses),
   - ⇒ Cross structures : regulators, falls, etc.
2. ***Analysis of the hydraulic data :***
   - ⇒ Discharge and water surface level distributions in the system,
   - ⇒ Implementation, calibration and validation of the hydraulic numerical model.
3. ***Analysis of the sedimentologic data :***
   - ⇒ Sediment concentration distribution in the system,
   - ⇒ Implementation, calibration and validation of the sedimentologic numerical model.
4. ***Diagnosis of the rules :***
   - ⇒ Diagnosis by simulation of the applied rules,
   - ⇒ Understanding and putting forward of the problematic of the system.
5. ***Proposition of alternative rules :***
   - ⇒ Test of alternative rules according to the problematic of the system,
   - ⇒ Presentation of the alternative rules.

6. ***a. Definition of criterias of choice of alternative rules :***
   ⇒ Definition of the constraints of the system,
   ⇒ Comparison between these constraints and the alternative proposed rules,
   → Putting forward of the applicability of the alternative rules.

   b. Comparison of the alternative rules :
   It consist of the comparison and classification of the alternative rules according to the previous criterias and their test by simulation.

   c. Selection of a set of alternative rules :
   It consists of the selection of the best set of alternative rules according to the previous comparison.

5.1.3. SYNTHESISING SUMMARY OF METHODOLOGIES

Design	***Operation - Maintenance***
1. Hydraulic and sedimentologic analysis. ***2. Sizing of the canal (empirical rules).*** ***3. Construction of the numerical models : hydraulic + sedimentologic.*** ***4. Test by simulation and correction of the sizing.***	***1. Analysis of the system.*** ***2. Analysis of the hydraulic data : construction of the numerical model.*** ***3. Analysis of the sedimentologic data : construction of the numerical model.*** ***4. Diagnosis of the rules by simulation.*** ***5. Proposition of alternative rules : test and presentation.*** ***6. a. Definition of criterias for the choice of alternative rules.*** ***b. Comparison, according to the criterias, of the alternative rules.*** ***c. Selection of the best set of rules and elaboration of recommendations of use.***

Synthesising summary of methodologies

5.2. CASE STUDIES OF IRRIGATION CANALS

5.2.1. INTRODUCTION

In order to minimise interpretation errors of the physical phenomenons on an actual case of irrigation canal, schematic case studies are chosen in this development work of methodologies for design, operation and maintenance. The selected cases are : a single reach (see *5.2.3.1.*), a single and double reaches with downstream regulating structures (see respectively *5.2.3.2.* and *5.2.3.3.*).

The main objective is to obtain a good understanding of the phenomenons of sediment equilibrium, deposition, and erosion in ideal cases, i.e. known initial topography and geometry, and then to develop general methodologies for design, operation and maintenance on irrigation canals subject to sediment problems.

Nevertheless, topographic, hydrologic and sedimentologic data have been borrowed to an actual case of irrigation canal (CRBC, Chashma Right Bank Canal, North West Frontier Province and Punjab, Pakistan) and have been averaged and linerarised (see *5.2.2.*) to identify a typical functioning year of the canal.

5.2.2. DATA

As already mentioned (see *5.2.1.*), topographic, hydrologic and sedimentologic data are borrowed to the CRBC actual case of irrigation canal.

The hydrologic and sedimentologic data have been observed during 4 years of functioning of the canal and are supposed representative of the future hydrologic and sedimentologic evolutions. It is an hypothesis that should be well respected for the discharge where the crop requirements are almost constant for each period of the year (or with low variations), but may present problems for sediment concentrations, especially for important events of sediments in the feeding river.

5.2.2.1. GENERAL DATA

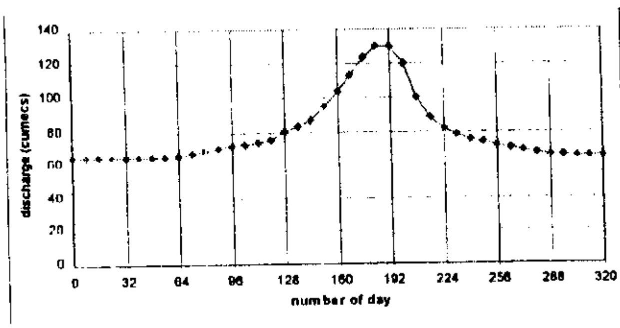
The main characteristics of the CRBC actual case of irrigation canal are :

⇒ Earthen canal,
⇒ Design realised according to the regime method through Lacey's formulas (see 2.2.1.) with an oversizing which allow sediment deposition (towards Lacey equilibrium) in order to decrease seepage losses,
⇒ Lacey silt factor *f* (see *2.1.1.*) calibrated for canals of the area at $f=0.96$,
⇒ Design discharge : about $130\ m^3/s$, for the studied portion of the canal,
⇒ Length : each studied reach is about *40 km*,
⇒ Section shape : trapezoidal with a side slope of 0.5/1,
⇒ Bed bottom width : about *50-60 m*, for the studied portion of the canal,
⇒ Uniform water depth : about *2.6 m*, for the studied portion of the canal,
⇒ Natural ground slope : $1.25 \cdot 10^{-4}$, for the studied portion of the canal.

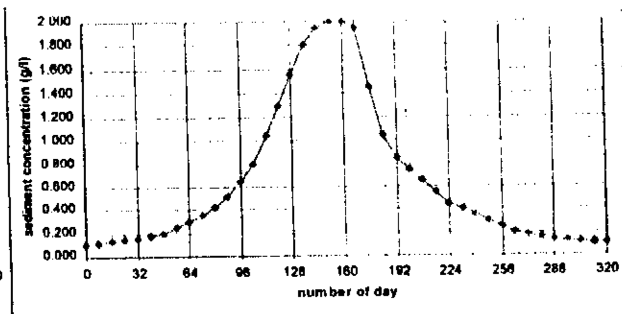
More details are provided in *6.1.* concerning the application on CRBC.

5.2.2.2. HYDROLOGIC AND SEDIMENTOLOGIC DATA

The average evolution (mean on 4 years) of the discharge and sediment concentration at the head of the canal during 1 year is as below :



Average hydrology during the year



Average sedimentology during the year

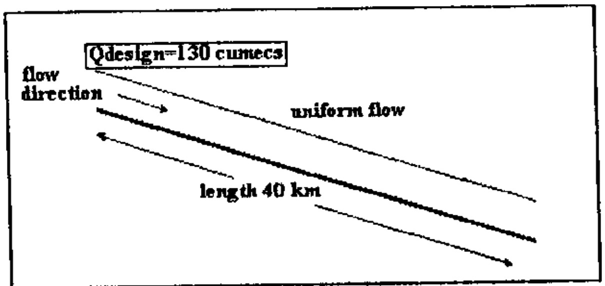
The mean values of the discharge and sediment concentration are respectively $80\ m^3/s$ and $0.650\ kg/m^3$ (or *g/l*) during the year. The duration of canal functioning period is 320 days because of the annual closure of every canal in Pakistan during 1 month (from mid-December to mid-January).

Variations of the discharge feeding the canal is due to the crop based system of functioning of this canal, this is a unique case in Pakistan, indeed canals are always functioning at the full supply discharge according to the design method : regime one (see *2.2.1.*). The next methodologies are testing the influence of this choice in the rate of sedimentation of the canals.

5.2.3. SCHEMATIC CANALS

5.2.3.1. CASE A : SINGLE LINEAR REACH

This case is used to study the behaviour of an irrigation canal composed of a single reach, in uniform conditions of hydraulic flow, and under different hydrologic and sediment constraints, i.e. design, mean or variable ones. The case study A can be described as below :

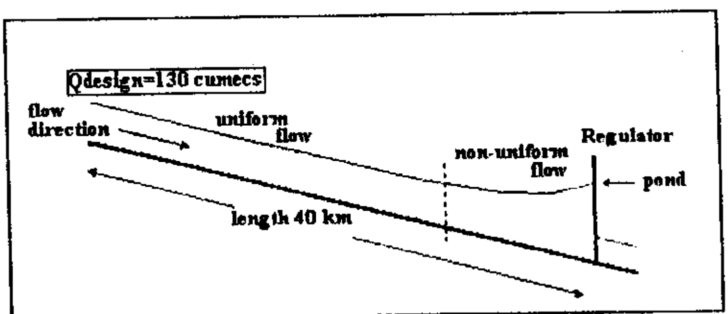


Schematic description of the 1st system : Case A

Cross sections of the reach have been designed in equilibrium conditions according to the regime method (see *2.2.1.*), more details are provided in Appendix 5. The goal of the next work is to verify (and criticise) the behaviour of the obtained topographic and geometric equilibriums through the simulation of the canal functioning during a long period (10 years) and under different hydrologic and sedimentologic constraints.

5.2.3.2. CASE B : SINGLE LINEAR REACH WITH A STRUCTURE

This case is used to study the influence of the introduction of a cross structure within an irrigation canal composed of a single reach under different hydrologic and sediment constraints, i.e. design, mean or variable ones. The chosen cross structure is a regulator, located downstream of the reach, and maintaining a pond at a value *50 cm* above the uniform regime (design discharge). The case study B can be described as below :



Schematic description of the 2nd system : Case B

Cross sections of the canal have been designed in equilibrium conditions according to the regime method (see *2.2.1.*), more details are provided in Appendix 5. The goal of the next work is to verify (and criticise) the behaviour of the obtained topographic and geometric equilibriums through the simulation of the canal functioning during a long period (10 to 20 years) and under different hydrologic and sedimentologic constraints.