INTER-DEPARTMENT PROGRAM OF POSTGRADUATE STUDIES IN WATER RESOURCES SCIENCE AND TECHNOLOGY

Postgraduate thesis:

Analysis of a past irrigation system in Oman

by Themis-Dimitra Xanthopoulou

Supervisor: Dr Demetris Koutsoyiannis, Professor at NTUA

External supervisor: Dr Maurits W. Ertsen, Associate Professor at TU Delft

Committee:

Dr Evangelos Baltas, Associate Professor at NTUA

Dr Nikos Mamassis, Assistant Professor at NTUA

October, 2015

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To Zoi and Dimitris

"I am the master of my fate:
I am the captain of my soul"

From Invitctus by William Ernest Henley

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Firstly, I would like to thank the Onassis Foundation for supporting my studies and making it possible for me to conduct this thesis in co-operation with the Technical University of Delft and Leiden University. Secondly, I think words are not able to express how grateful I am to Dr Maurits Ertsen for all the new concepts I learned from him, his support and also for his excellent supervision. I am also really thankful to Dr Demetris Koutsoyannis, for giving me the opportunity to select this topic, for helping me in the process but more than that for his lectures; a combination of engineering and philosophy. Furthermore, this research would not have happened without the data gathered from the Leiden team. Special thanks to Dr Bleda During and Sufyan Al Karaimeh. During the process of my research, I received help from Jianzhi Dong and Ante Zoric and I want to thank them both very much.

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Preface

According to FAO, one third of the world's total population lives in arid environments. The climate has been always changing and in combination with human's intervention in the ecosystems more regions face common challenges with the arid regions.

Studying present water systems can give insights about the options available to different cases in respect to water management as well as challenges in operating one. Studying past systems gives on the other hand a broader view about the complexity of each system. A water system is the child of specific environmental and societal conditions. The first form of system is a reflection of both of them. However, as time progresses, interactions begin to happen between the three of them. Eventually, the system shapes its surroundings, both human and non-human and the limitations of the triptych are challenged. The interactions are the most important factor in the endurance of the system and they can only be studied and understood in the depth of time.

The water system of focus was never studied before and thus the first analysis performed in this project serves to limit the framework in which the system was operating.

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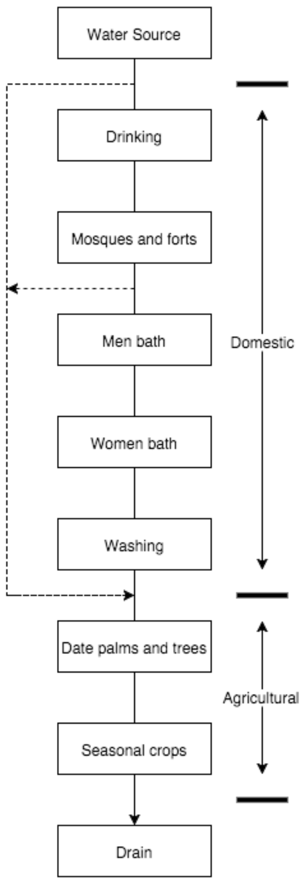
Abstract

An archaeological field study led to the gathering of data for a past Omani irrigation system of the 16th-17th century. The system was supplied with water from a main water system (falaj systm) and the cross-section in the water system is well preserved. Hydraulic modeling was selected in order to understand the interactions between the system-the environment and the human agent. The water demand is not known but it can be estimated with assumptions regarding the crops, the soil and the agricultural practices. Two scenarios on the input flow in the system were made and in the hydraulic modeling different irrigation management scenarios were implemented. From the modeling results, it can be concluded that the system needed hydraulic structures for irrigation in all fields to be possible. From the hydraulic simulation and the water balance in the fields, stones that divert water are placed in the fields after the completion of irrigation. The stone settings reveal that the system needed co-operation from the inhabitants to work in order to satisfy the water needs. If parallel irrigation in combination with hydraulic structures is performed then the irrigation duration lowers but more farmers are needed. If the fields are irrigated separately, less human force is needed but the irrigation duration raises a lot. Power relations between canal systems, between the intakes of water from the main system and between fields systems are reasons to believe that conflict had to be resolved between the users of the system. Finally, potential locations for intake of domestic use and perennial crops were identified based on the priorities directed by traditional agriculture.

Εκτενής Περίληψη

Εισαγωγή

Η περιοχή του Βόρειου Ομάν χαρακτηρίζεται από ξηρό κλίμα (Wikipedia.org). Από τα αρχαία χρόνια όμως, οι κάτοικοι έχουν καταφέρει να καλλιεργούν μεγάλες εκτάσεις με την κατασκευή ειδικών συστημάτων μεταφοράς νερού, τα aflaj (ενικός:aflaj) (Al-Ghafri et al, 2003). Πιο συγκεκριμένα, εώς και την τωρινή εποχή τα συστήματα χρησιμοποιούν είτε το νερό που συλλέγεται στα βουνά είτε το εποχικό νερό στα λεγόμενα wadi. Στην περίπτωση συλλογής υπογείου νερού, το σύστημα κατασκευής (γνωστό και ως qanat) αποτελείται από στοές σε υδατοπερατό πέτρωμα με κατακόρυφα τούνελ για αερισμό και επισκευές που εξελίσσονται σε ανοικτούς αγωγούς για την μεταφορά του νερού στις καλλιεργήσιμες εκτάσεις (Shahalam, 2000). Στην περίπτωση που το νερό συλλέγεται από πηγές στα βουνά, το σύστημα αποτελείται από τους αγωγούς μεταφοράς που καταλήγουν στους οικισμούς ενώ τέλος αν το σύστημα τροφοδοτείται από εποχικό νερό τότε αποτελείται από αγωγούς εκτροπής. Τα συστήματα διανέμουν το νερό με προτεραιότητα στην οικιακή χρήση όπως φαίνεται από το παρακάτω σχήμα:



Σχήμα 1. Προτεραιότητα χρήσης νερού σε σύστημα falaj. (Πηγή: Shahalam, 2000)

Η περιοχή λόγω του ενδιαφέροντος που παρουσιάζει κίνησε την προσοχή αρχαιολογικών ομάδων. Μία από αυτές είναι η αρχαιολογικές ομάδα του Πανεπιστημίου του Leiden, η οποία συνέλεξε δεδομένα από ένα αρδευτικό σύστημα βαρύτητας της περιοχής με απώτερο σκοπό την κατανόηση της καθημερινής ζωής των κατοίκων την προηγούμενη χιλιετία σε ένα οριακά ερημικό περιβάλλον όπως αυτό.

Η κατασκευή του συστήματος άρδευσης χρονολογείται τον 16^{o}-17^{o} μΧ αιώνα και η εγκατάλειψή του στις αρχές του $20^{ου}$ αιώνα (Costa and Wilkinson, 1987). Η περιοχή βρίσκεται ανάμεσα στα βουνά και στην παραθαλάσσια πόλη Σοχάρ. Το σύστημα τροφοδοτείται με νερό από ένα falaj το οποίο ενώνει τα βουνά με την Σοχάρ. Το είδος υδατικού πόρου από τον οποίο τροφοδοτείται δεν είναι γνωστό καθώς η αρχή του συστήματος δεν έχει εντοπιστεί ακόμη. Εν τούτοις, η μεγάλη του έκταση (πάνω από 36,5km) και το γεγονός ότι δεν έχει βρεθεί κάποιος αγωγός εκτροπής παραπέμπουν σε σύστημα που τροφοδοτείται από υπόγειο νερό ή από νερό πηγής. Τα δύο συστήματα αυτά έχουν πιο σταθερή ροή όλο τον χρόνο. Την ίδια περίοδο φαίνεται ότι λειτουργούσαν δύο άλλα συστήματα που βρίσκονται κατάντη αυτού του συστήματος άρδευσης, τα οποία χρησιμοποιούν και αυτά νερό από το falaj.

Η παρούσα εργασία αποσκοπεί στην υποβοήθηση των στόχων της αρχαιολογικής έρευνας. Πιο συγκεκριμένα, οι στόχοι αυτοί είναι η κατανόηση των αλληλεπιδράσεων των κατοίκων με το σύστημα, ο εντοπισμός πιθανών προβλημάτων που μπορεί να αντιμετώπιζαν καθώς και η εμβάθυνση στις σχέσεις συνεργασίας που απαιτεί το σύστημα για την επιτυχή καλλιέργεια καρπών.

Αρχικά θα γίνει αναφορά συνοπτικά στο θεωρητικό υπόβαθρο στο οποίο βασίζεται η εργασία. Στην συνέχεια αναλύεται συνοπτικά η μεθοδολογία που χρησιμοποιήθηκε, το εννοιολογικό μοντέλο καθώς και οι παραμέτροι που δεν λήφθηκαν υπόψει. Μετά παρουσιάζονται και ερμηνεύονται τα αποτελέσματα από το λογισμικό Sobek 1D και από την ανάλυση δεδομένων. Τέλος δίνεται μία συνοπτική παρουσίαση των συμπερασμάτων από την συνολική έρευνα.

Θεωρητικό υπόβαθρο της εργασίας

Η εργασία βασίζεται στην δουλειά του κοινωνιολόγου Bruno Latour. O Latour (Latour, 1996) υποστηρίζει ότι για την κατανόηση των αλληλεπιδράσεων σε μία κοινωνία πρέπει να εστιάσουμε στα αντικείμενα που χρησιμοποιούνται. Ο όρος αντικείμενα χρησιμοποιείται για κάθε τι που έχει υλικές διαστάσεις και ιδιότητες. Τα αντικείμενα αλληλοεπιδρούν υλικά αλλά και πολιτιστικά με τον άνθρωπο μέσω των πεποιθήσεων που έχει για αυτά και συνεπώς η ύπαρξη τους οριοθετεί τις αλληλεπιδράσεις. Η υλοποίηση της άρδευσης στην περίπτωσή ενός αρδευτικού συστήματος πρέπει να πραγματοποιηθεί μέσω των συγκεκριμένων καναλιών και του συγκεκριμένου εδάφους με σκοπό να αρδεύσει τα συγκεκριμένα χωράφια. Ο Έρτσεν (2010), προτείνει την χρησιμοποίηση της υδραυλικής μοντελοποίησης ως μεθοδολογία σύνδεσης των αντικειμένων με τον ανθρώπινο παράγοντα.

Το σύστημα

Το σύστημα (Σχήμα 2) τροφοδοτείται από το falaj σε 2 σημεία.

Σχήμα 2. Το αρδευτικό σύστημα.

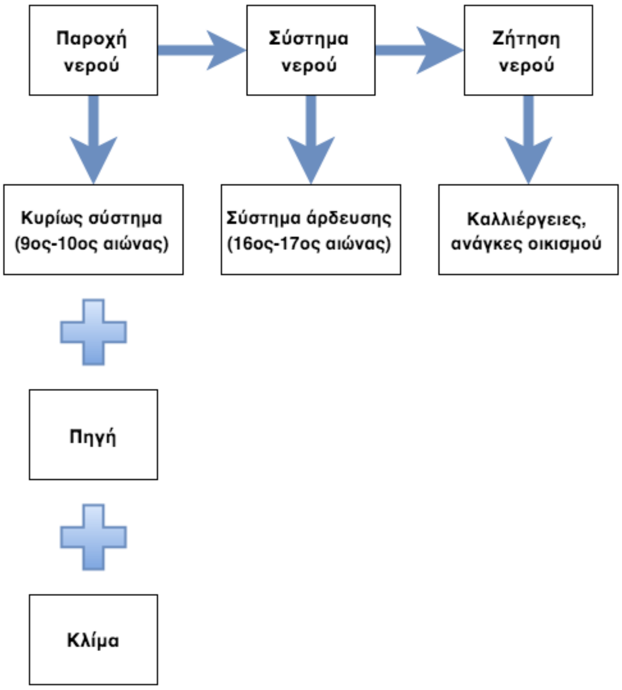
Μεθοδολογία

Η μεθοδολογία αποτελείται από την ανάλυση των δεδομένων ως έχουν και την μοντελοποίηση στο υδραυλικό μοντέλο Sobek. Τα δεδομένα που έχουν δοθεί για την πραγματοποίηση αναλύσεων είναι τα υψομετρικά στοιχεία της περιοχής, οι διαστάσεις των καναλιών του αρδευτικού συστήματος και του falaj, φωτογραφίες για την κατανόηση της διάταξης του συστήματος, η τοποθεσία πετρών που έχουν χρησιμοποιηθεί για την οριοθέτηση των χωραφιών, η τοποθεσία κάποιων τειχών στο σύστημα και η τοποθεσία κτιρίων του οικισμού.

Ανάλυση Αρχικών δεδομένων

Η ανάλυση των αρχικών δεδομένων περιλαμβάνει την σύγκριση των υψομετρικών δεδομένων με την τοποθεσία των καναλιών και των χωραφιών. Αυτό αποσκοπεί αρχικά στον εντοπισμό των σχέσεων εξάρτησης των χωραφιών όταν ο τρόπος τροφοδότησης του νερού είναι από χωράφι σε χωράφι και κατά δεύτερον στην ομαδοποίηση των χωραφιών που τροφοδοτούνται από ένα συγκεκριμένο σύστημα καναλιών. Επίσης, το γεγονός ότι το σύστημα τροφοδοτεί τα χωράφια μέσω βαρύτητας δεν σημαίνει ότι όλα τα κανάλια έχουν λόγο ύπαρξης καθώς η κατασκευή κάποιων από αυτά δυνητικά μπορεί να είχε αποφευχθεί από την επέκταση άλλων συστημάτων. Η ανάλυση αυτή σκοπεύει ακόμη στο να κατανοήσει την χρησιμότητα του κάθε συστήματος καναλιών. Οι ομαδοποιήσεις που γίνονται στην συνέχεια χρησιμοποιούνται στο στήσιμο του μοντέλου.

Εννοιολογικό μοντέλο, Βήματα Μοντελοποίησηςκαι Μέθοδος Επεξεργασίας Αποτελεσμάτων



Σχήμα 3. Γενικό σχήμα άρδευσης.

Στην περίπτωση του εξεταζόμενου συστήματος δεν είναι γνωστές ούτε οι παράμετροι που σχετίζονται με την προσφορά νερού ούτε αυτές που σχετίζονται με την ζήτηση. Η αβεβαιότητα της ζήτησης αντιμετωπίζεται με την δημιουργία σεναρίων. Οι καλά διατηρημένες διαστάσεις της διατομής του falaj πριν του σημείου εκτροπής του νερού στο σύστημα άρδευσης καθιστούν εφικτή την περιγραφή των σεναρίων σε συνάρτηση με το μέγιστο επίπεδο νερού που επιτρέπεται στο κανάλι. Για την αντιμετώπιση της αβεβαιότητας της ζήτησης, η οποία ισούται με τις ανάγκες των φυτών που καλλιεργούνται, επιλέγεται ως αντιπροσωπευτικός καρπός του συστήματος το σιτάρι. Μία πρόσφατη έρευνα σε περιοχή κοντά στο αρδευτικό σύστημα για τις ανάγκες σε νερό σιταριού δίνει μία καλή εκτίμηση (Norman et al, 1997). Επίσης γίνεται η υπόθεση ότι η άρδευση επαναλαμβάνεται κάθε 10 μέρες. Προφανώς αναγνωρίζεται ότι οι ανάγκες των καρπών σε νερό, λόγω γενετικών τροποποιήσεων, έχουν αλλάξει σε σχέση με τον 16^{o} αιώνα (Zhu et al, 2015). Επίσης προφανώς το σιτάρι δεν θα ήταν ο μόνος καρπός που καλλιεργείτο. Εν τούτοις για λόγους απλοποίησης η επιλογή θεωρείται καλή.

Μία άλλη παράμετρος που επηρεάζει την άρδευση είναι το έδαφος. Το έδαφος αντιπροσωπεύεται στο μοντέλο από τον ρυθμό διήθησης του νερού. Σαν επιλογή εδάφους επιλέχθηκε ένα λασπώδες έδαφος το οποίο φαίνεται ότι υπάρχει στην περιοχή(FAOa). Ένας άλλος λόγος είναι οι παρατηρήσεις των αρχαιολόγων παραπέμπουν σε εύφορο έδαφος αποκλείοντας την πιθανότητα το έδαφος να είναι άργιλος ή άμμος. Η διήθηση επηρεάζεται και από τον χρόνο της άρδευσης όπως και από την παροχή νερού. Όμως, η ανάλυση ευαισθησίας που πραγματοποιήθηκε έδειξε ότι οι συγκεκριμένες παράμετροι παίζουν μικρότερο ρόλο από το είδος του εδάφους.

Στο μοντέλο υπεισέρχεται και η μέθοδος άρδευσης. Πιο συγκεκριμένα στην υδραυλική μοντελοποίηση εξετάζονται:

Α) Η παράλληλη άρδευση όλων των χωραφιών

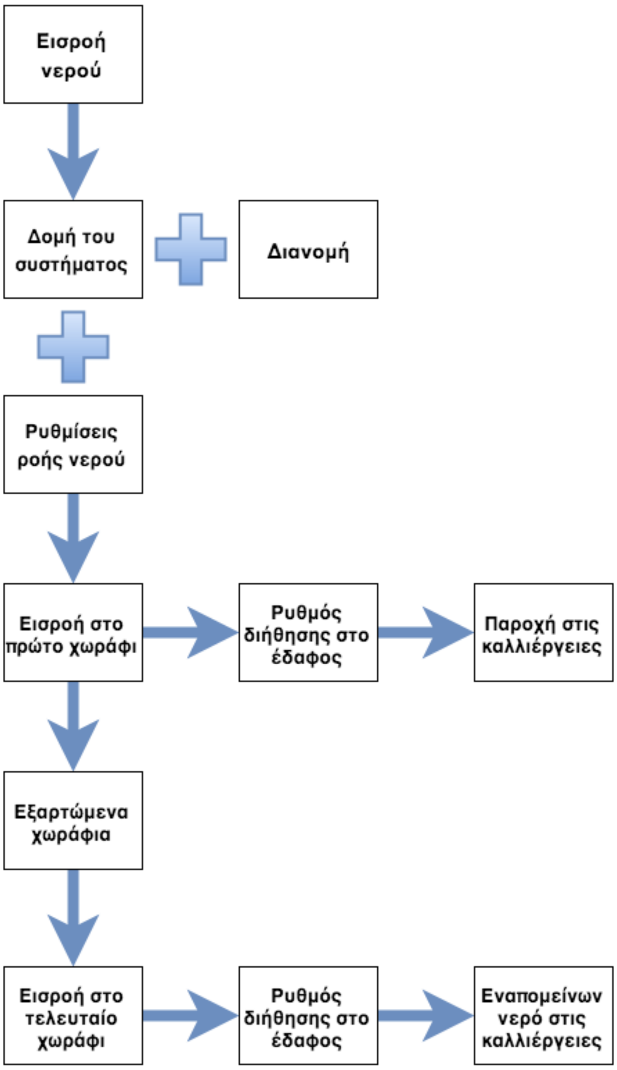
Β) Η άρδευση από τα ανάντη χωράφια στα κατάντη. Η τροφοδότηση μπορεί να αφορά όλο το σύστημα ή ενα σύστημα καναλιών.

Γ) Η άρδευση από τα κατάντη χωράφια στα ανάντη. Η τροφοδότηση μπορεί να αφορά όλο το σύστημα ή ενα σύστημα καναλιών.

Δ) Η άρδευση σε ομάδες χωραφιών που τροφοδοτούνται από το ίδιο κανάλι με την τεχνική από τα ανάντη στα κατάντη

Για την εφαρμογή των Β,Γ,Δ τοποθετούνται πύλες στο σύστημα. Στις παραδοσιακές πρακτικές τον ρόλο των πυλών παίζουν πέτρες.

Παράμετροι που δεν λήφθηκαν υπόψει είναι η εξάτμιση στα κανάλια, η διήθηση στα κανάλια, η παρουσία των φερτών υλικών και τέλος οι αλλαγές στην ζήτηση του νερού λόγω διαφορετικού στόχου σοδειάς.



Σχήμα 4. Διανοητικό μοντέλο.

Στο μοντέλο επιλέγουμε να εισάγουμε όλα τα χωράφια που υπάρχουν έτσι ώστε τα αποτελέσματα να είναι αντιπροσωπευτικά ως προς την κατανομή των ροών και να εμφανιστούν σχέσεις προτεραιότητας μεταξύ τους. Όταν τα χωράφια δεν τροφοδοτούνται από κανάλι εκροής έχουν επαφή με ένα κανάλι και υπάρχει η δυνατότητα να τροφοδοτηθούν από αυτό μέσω της βαρύτητας. Σε αυτή την περίπτωση θεωρείται ότι μία πέτρα από το κανάλι αφαιρείται έτσι ώστε να επιτευχθεί η άρδευση του καναλιού. Στην περίπτωση που δεν υπάρχει επαφή με κανάλι, τότε το χωράφι ανήκει σε μια ομάδα χωραφιών τα οποία τροφοδοτούν το ένα το άλλο. Ο τρόπος τροφοδότησης, δεδομένου ότι δεν έχει βρεθεί κάποιο χωμάτινο κανάλι, θεωρείται ότι γίνεται μέσω της αφαίρεσης μίας πέτρας από αυτές που οριοθετούν το χωράφι.

Στο σημείο αυτό πρέπει να διευκρινιστεί ότι στις προσομοιώσεις θεωρήθηκε ότι όταν ξεκινάει η άρδευση όλα τα πιθανά περάσματα, είτε από χωράφι σε χωράφι, είτε από κανάλι σε χωράφι είναι ανοιχτά. Ακόμη, το αρδευτικό σύστημα χωρίστηκε σε ενότητες όπου μία ενότητα αποτελεί ένα σύστημα καναλιών όπως αυτό έχει ορισθεί από τους αρχαιολόγους.

Έτσι έχουμε τα συστήματα B,C,D,E,F,G και H. Κάποια από αυτά τα συστήματα κλείνουν με την βοήθεια πυλών με σκοπό την εμβάθυνση στον τρόπο που λειτουργεί το σύστημα.

Για την προσομοίωση των σεναρίων στα οποία τα χωράφια αρδεύονται παράλληλα ακολουθούνται τα παρακάτω βήματα:

I. Επιλογή σεναρίου εισροής νερού (20% ή 80% της μέγιστης δυνατής)
II. Προσομοίωση με το λογισμικό Sobek
III. Καταγραφή των ροών σε κάθε χωράφι ξεχωριστά

Στις περιπτώσεις Β και Γ όπου η άρδευση γίνεται από τα ανάντη στα κατάντη και το αντίστροφο ακολουθείται η διαδικασία:

I. Επιλογή σεναρίου εισροής νερού (20% ή 80% της μέγιστης δυνατής)
II. Προσομοίωση με το λογισμικό Sobek
III. Καταγραφή της ροής είτε στο πιο ανάντη είτε στο πιο κατάντη χωράφι (ανάλογα με την μέθοδο άρδευσης)
IV. Εφαρμογή υδατικού ισοζυγίου για την εύρεση της διάρκειας της άρδευσης χρησιμοποιώντας την χρονοσειρά των εισροών, την χρονοσειρά των εκροών (αν το χωράφι τροφοδοτεί άλλο χωράφι), τον ρυθμό διήθησης και την απαιτούμενη ποσότητα νερού.
V. Τοποθέτηση πέτρας-πύλης στο σημείο παροχής του νερου για να σταματήσει η ροή προς το χωράφι.
VI. Προσομοίωση με το λογισμικό για τον υπολογισμών των νέων ροών μετά την τοποθέτηση της πέτρας.
VII. Καταγραφή της ροής στο αμέσως επόμενο ή αμέσως προηγούμενο χωράφι (ανάλογα με την μέθοδο άρδευσης).
VIII. Συνέχιση της διαδικασίας όπως περιγράφηκε πριν με τον υπολογισμό του υδατικού ισοζυγίου και την τοποθέτηση πέτρας πύλης όταν έχει ικανοποιηθεί η ζήτηση νερού από το κανάλι.
IX. Όταν ολοκληρωθεί η άρδευση όλων των χωραφιών που τροφοδοτούνται από ένα κανάλι το κανάλι κλείνει με πέτρα-πύλη.

Η περίπτωση Δ μοιάζει με την περίπτωση Γ με την διαφορά ότι υπάρχει μία πέτρα πύλη η οποία αποτρέπει την παροχέτευση των κατάντη χωράφιων ώστε να μείνει το νερό στην επιθυμητή ομάδα χωραφιών. Όταν ολοκληρωθεί η άρδευση στην όμαδα τότε η πύλη ανοίγει για να παροχετευθεί η επόμενη ομάδα με τον ίδιο τρόπο.

Στην προσπάθεια εύρεσης ενός τρόπου αναπαραγωγής αποτελεσμάτων χωρίς όμως την επίπονη διαδικασία της προσομοίωσης δημιουργήθηκε ο δείκτης IrrEf ο οποίος συνδέει την διάρκεια άρδευσης με την έκταση χωραφιών που συνδέονται με ένα κανάλι ή σύστημα καναλιών και την παροχή νερού σε αυτό. Πρακτικά θα μπορούσαμε να τον εξηγήσουμε ως ένα μετρό της απόδοσης με βάση τον χρόνο. Ο δείκτης ισούται με την διάρκεια ανηγμένη ως προς την έκταση των χωραφιών και την παροχή νερού.

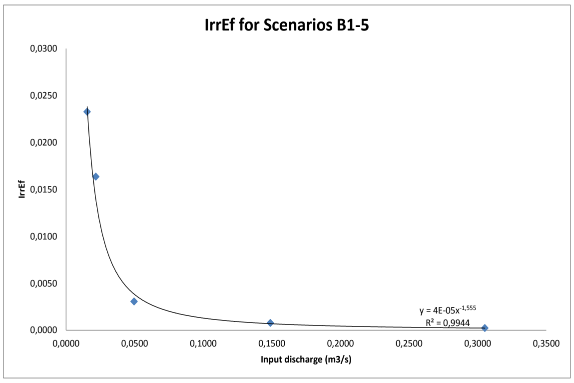
Αποτελέσματα

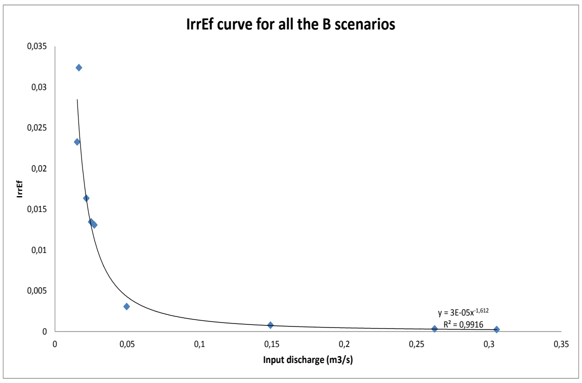
Τα αποτελέσματα παρουσιάζονται στον παρακάτω πίνακα:

Πίνακας 1. Αποτελέσματα από την χρήση του μοντέλου.

Σενάριο	Μέθοδος άρδευσης	Εισροή νερού στο σύστημα	Αποτελέσματα για σύστημα	Διάρκεια άρδευσης	Αριθμός πετρών-πυλών
	Παράλληλη άρδευση	80% της μέγιστης	Όλα	28 fields with no water	Κανένας
	Παράλληλη άρδευση	80% της μέγιστης	Όλα	130 fields with no water	Κανένας
Όλα τα συστήματα ανοιχτά	Από τα ανάντη στα κατάντη	80% της μέγιστης	C	112 min	19
Όλα τα συστήματα ανοιχτά	Από τα ανάντη στα κατάντη	80% της μέγιστης	H	372min	33
Όλα τα συστήματα ανοιχτά εκτός από το H	Από τα ανάντη στα κατάντη	80% της μέγιστης	C	48min	16
Όλα τα συστήματα ανοιχτά εκτός από το H	Από τα ανάντη στα κατάντη	80% της μέγιστης	B	97min	31
Εισροή 1 κλειστή και H κλειστό	Από τα ανάντη στα κατάντη	80% της μέγιστης	C	36min	17
Όλα κλειστά εκτός από το C	Από τα ανάντη στα κατάντη	80% της μέγιστης	C	22min	16
Εισροή 1 κλειστή και H κλειστό	Από τα ανάντη στα κατάντη	20% της μέγιστης	C	113min	17
Εισροή 1 κλειστή και C κλειστό	Από τα ανάντη στα κατάντη	20% της μέγιστης	H	560min	33
Ανοιχτό μόνο το B στην εισροή 1	Από τα ανάντη στα κατάντη	20% της μέγιστης	B	396min	31
Ανοιχτό μόνο το B στην εισροή 1	Άρδευση σε ομάδες χωράφιων	20% της μέγιστης	B	580min	31

Ο δείκτης IrrEf υπολογίστηκε για το σύστημα καναλιών C και την τεχνική άρδευσης (από ανάντη στα κατάντη) δεδομένου ότι υπάρχουν πολλές προσομοιώσεις για το σύστημα. Η καμπύλη IrrEf-παροχή που περνάει από τα σημεία δίνει μια πολύ καλή προσέγγιση. Εάν προσθέσουμε και τα αποτελέσματα των προσομοιώσεων από τα άλλα συστήματα καναλιών με την ίδια τεχνική φαίνεται ότι η καμπύλη μπορεί να περιγράψει και αυτά. Συνεπώς, δεδομένου μίας παροχής μπορούμε να βρούμε την τιμή του συντελεστή και στην συνέχεια την διάρκεια της άρδευσης για την ίδια παροχή και για μία συγκεκριμένη έκταση. Η διάρκεια αυτή αντιστοιχεί στην τεχνική άρδευσης από ανάντη στα κατάντη με την χρησιμοποίηση πετρών-πυλών.





Σχήμα 5. Διάγραμματα IrrEf-παροχή για το σύστημα καναλιών C (αριστερά) και για τα όλες τις περιπτώσεις (δεξιά)

Με τον δείκτη αυτόν έγινε δυνατή η εκτίμηση της συνολικής διάρκειας της άρδευσης για όλο το σύστημα με 2 μεθόδους. Στην πρώτη μέθοδο, η άρδευση γίνεται από ανάντη στα κατάντη για όλα τα συστήματα παράλληλα ενώ στην δεύτερη από ανάντη στα κατάντη για κάθε σύστημα ξεχωριστά . Είναι εμφανής η μεγάλη διαφορά στην διάρκεια άρδευσης λόγω διαφορετικής τεχνικής.

Πίνακας 2. Αποτελέσματα για την συνολική διάρκεια της άρδευσης.

Μέθοδος	Εισροή νερού σο σύστημα	Διάρκεια άρδευσης	Αριθμός πετρών-πυλών
1	80% της μέγιστης	2h39min	125
1	20% της μέγιστης	11h26min	125
2	80% της μέγιστης	5h4min	125
2	20% της μέγιστης	21h50min	125

Συμπεράσματα

Για τις σχέσεις εξουσίας

- Από τις προσομοιώσεις και την τοποθέτηση των πετρών-πυλών, είναι εμφανές ότι στις περιπτώσεις που έχουμε τροφοδότηση νερού από χωράφι σε χωράφι, το ανάντη χωράφι ασκεί εξουσία στα κατάντη χωράφια.
- Το πρώτο σημείο παροχέτευσης είναι υδραυλικά ανεξάρτητο από το δεύτερο ενώ το δεύτερο εξαρτάται από το πρώτο. Το αποτέλεσμα μπορεί να ερμηνευθεί και σε σχέση με τους χρήστες του νερού των δύο παροχετεύσεων. Όποιος έχει έλεγχο στο πρώτο σημείο παροχέτευσης μπορεί να ασκήσει έλεγχο στο δεύτερο και σε όλους τους χρήστες του.
- Από την ανάλυση των ροών φαίνεται ότι δύο συστήματα έχουν εγγενή προτεραιότητα στην άρδευση το F και το E.

Συμπέρασμα: Οι σχέσεις εξουσίας σε ένα σύστημα, δεδομένης της φύσης των ανθρώπων, δημιουργούν αιτίες συγκρούσεων στους αγρότες. Για την ομαλή συμβίωση των κατοίκων του συστήματος, κάποιου είδους τοπική αρχή είναι αναγκαία ώστε να τηρούνται κανόνες χρήσης του νερού.

Για τα κατάντη αρδευτικά συστήματα

- Όταν είναι ανοιχτές οι 2 παροχετεύσεις του αρδευτικού συστήματος, δεσμεύεται στο σύστημα μέχρι και το 90% του νερού που κυλά στο falaj. Συνεπώς, εκείνο το διάστημα οι χρήστες των κατάντη αρδευτικών συστημάτων δεν μπορούν να εκμεταλλευτούν το νερό για άρδευση της τάξης που ερευνήθηκε.
- Η διάρκεια της άρδευσης, για τα είδη άρδευσης που προσομοιώθηκαν, είναι κατά το μέγιστο της τάξης της μίας μέρας στις 10 μέρες (που αντιστοιχεί στην περίοδο της άρδευσης). Συνεπώς, η χρήση του νερού από το σύστημα δεν αποτρέπει την χρήση του νερού από τα κατάντη συστήματα εφόσον δεν γίνεται την ίδια στιγμή.

Συμπέρασμα: Διαφαίνεται η ανάγκη ύπαρξης κάποιας συνεννόησης μεταξύ του αρδευτικού συστήματος και των κατάντη αρδευτικών συστημάτων. Παράλληλα, είναι σημαντικό να τονιστεί η θέση προτεραιότητας και άρα και εξουσίας που έχει το σύστημα σε σχέση με τα κατάντη αρδευτικά συστήματα.

Για την μέθοδο άρδευσης

- Στο σενάριο των μεγαλύτερων παροχών εισροής νερού, ένα σύστημα καναλιών (το σύστημα Η) υπερχειλίζει αν προσπαθήσουμε να απομονώσουμε την άρδευση σε αυτό.
- Στην περίπτωση που η άρδευση γίνεται παράλληλα σε όλα τα χωράφια χωρίς εφαρμογή πετρών-πυλών, κάποια χωράφια υπερχειλίζουν ενώ άλλα που βρίσκονται σε πιο χαμηλά υψόμετρα δεν λαμβάνουν καθόλου νερό. Σε χαμηλές παροχές νερού πάνω από το 1/3 των χωραφιών δεν δέχεται νερό.
- Όσο πιο πολλά συστήματα αρδεύονται παράλληλα με την εφαρμογή πετρών-πυλών, τόσο μειώνεται ο συνολικός χρόνος της άρδευσης του συστήματος ενώ αυξάνονται οι πέτρες-πύλες που πρέπει να τοποθετηθούν από τους χρήστες του συστήματος σε μία συγκεκριμένη χρονική περίοδο.
- Η χρησιμοποίηση περισσότερων μηχανισμών ελέγχου δεν αποφέρει απαραίτητα μείωση της διάρκειας της άρδευσης ακόμη και στο ίδιο σύστημα.

Συμπέρασμα: Είναι η απαραίτητη η χρήση πετρών-πυλών για την αποτελεσματική άρδευση όλων των χωραφιών. Σε σχέση με την πρακτική άρδευσης οι αγρότες έχουν να επιλέξουν ανάμεσα σε μία χρονοβόρα πρακτική άρδευσης που όμως χρειάζεται λιγότερους ανθρώπους για να επιτευχθεί ή σε μία πρακτική η οποία μειώνει κατά πολύ την διάρκεια της άρδευσης αλλά απαιτεί την συμμετοχή πολλών ατόμων στο σύστημα, την καλή συνεργασία τους και τον καλό συντονισμό των κινήσεών τους.

1. Introduction

1.1 An archaeological expedition

In 2014, archeologists from the University of Leiden carried out an expedition. Before the expedition places of interest were identified with the help of satellite images. The region had not been researched in detail before. Among many interesting features from different eras, the irrigation system that is analyzed in this study stood out (Figure 1). The system is dated to the Islamic period. Water is provided by a main water system constructed between the 9th and 10th century A.D.

Figure 1. The irrigation system (Source: Google Earth)

A year later (2015) the area was revisited in order for researchers to gather more data. The most essential data concerning the irrigation system are the following:

- Elevation data: During the expedition elevation data were recorded with precision of cm in features of interest such as the canal bed and the fields.
- Photographs: Several photographs of the irrigation system were taken.
- Dimensions: In order to understand the irrigation practices in the region, systematic documentation was performed on the canal dimensions (with precision of 1 cm).
- Locations of buildings and structures: The location of the settlement structures and field structures was recorded.

1.2 Historical Background

In order to analyze the system, we searched for more information about the region and its history. The irrigation system is located on the hinterland of the Sohar region as shown on the map of Figure 2. The city of Sohar, which served as a port, was really prosperous (almost 12.000 houses) in the 10th century according to historians of that period (Williamson 1973). The port was located at a strategic point of a large trading route. Some of the regions that were involved in the trade were India, Africa and South Arabia. The political instability seems to be the cause of both the rapid rise and the rapid decline of the city. The flourish came either when the city was under the control of the Caliph of Baghdad or during a small independence period. Different empires including the Seljuk Turks, the Portuguese and the Persians controlled Oman until the 18th century when the region came under the hands of the local families (Yaruba and Al said dynasty).

Even though the physical properties of the coast do not favor the creation of a harbor, the region had an important asset (Williamson 1973). The wadi (Wadi Al Jizzi) that reaches the coast provides a natural connection between the mountains and the sea. In addition, it carries the water that the port needs in means of perennial waters and groundwater aquifer. It was in this wadi that a massive (up to 30km) water system was constructed (Costa and Wilkinson, 1987). The system, which is called falaj al Mutaridh, was used in the 10th century but probably was built in several stages. The stone water system has many features such as inverted siphons and mills and was probably used to supply water to the palm gardens near the Batinah coast. During this period, the palm gardens occupied an area four times larger than the modern ones. The system also provided water to travelers and merchants passing through the wadi and to nearby settlements. However, it is uncertain whether all these advantages justify the project’s enormous size and the required investment for its construction.

After the decline of the region, the water system did not function as it had in the previous years (Costa and Wilkinson, 1987). One theory is that it ceased to work in the 12th century. It is estimated, via indirect dating, that in the 17th century fields that were constructed in that period reused the system. The irrigation system of focus is the most upstream field system. According to estimations, the fields were abandoned in the 20th century. Miles (Miles, 1877) was the last to record the agricultural activity in the region and the usage of the water system.

Figure 2. Map of Oman (Source: http://www.lib.utexas.edu).

1.3 From water to humans

1.3.1 Theoretical background

The general goal of this project is to understand more about the way people lived in this settlement and, if possible, in the broader area. This corresponds to finding interactions happening inside this area on a daily basis. We consider interactions among people and the irrigation system, people and the general system, people and the environment and, if permitted by the data, the system and the environment. Furthermore, we try to get a glimpse of the societal aspects of this settlement.

While trying to identify the elements that make our society different than the society of other primates, a group of sociologists turns to interactions (Latour, 1996). Their method is to try to evolve the interactions into social construction. Another group of sociologists suggest that this is not possible because interactions can never escape the social structure surrounding them. Bruno Latour (1996), on the other hand, believes that both theories have a flaw. In both theories there is a presumptive gap between interactions and social structures. Also, they do not consider the difference between human interactions and those characterizing the primate ones. Human interactions are more isolated and can occur even when two persons are far away one from the other. Furthermore, two people can interact while acting on different times. What makes these interactions possible is the existence of objects. Primates do not use objects in the scale we do. This is why Latour proposes that we should use objects as a starting point of a social analysis leading to both interactions and social structure. But how can objects make such a difference? For a start, objects have material properties. These properties enable them to be used by people in order to replace their actions. Essentially, they do not imitate humans and their behavior cannot be predicted. In other words, objects are not mere reflections of agency and we should address them as agents themselves.

As to the argument that objects affect the social, objects interact physically and culturally with humans and bring recurrent themes to them (Strang, 2014). The result of the interaction cannot be deterministically derived and in the cultural level this happens because each culture gives different meanings to the recurrent themes. As a final statement, properties are always defined when we see an object in relation to something else. As water engineers, we are interested in water and we look into the relation between water and the structuring properties of the irrigation system.

1.3.2 From theory to practice

In order to put the theory into practice we need to come up with a method to link objects (structures in the system and water) to daily interactions. Ertsen (2010) has proven that for irrigation systems we can use the analysis of flows in the system to gain insights about the human agent. This can be achieved with hydraulic modeling. Hydraulic modeling shows how the flows are distributed in a water system locally and temporally. This is information we cannot extract from a water balance method of a water system. Flows can indicate possible problems in dealing with the system and thus are linked to the human agent.

1.4 Traditional agriculture in Oman

1.4.1 Aflaj

Traditional agriculture in Oman is achieved with the falaj system (plural: aflaj). The term means "a gap between two sides, a small creek or a small water conveying channel" (www.unep.or.jp). It is estimated that 3.095 aflaj systems still function while about 1.064 have been abandoned. Evidence shows that the first aflaj systems in Oman date back to 2500BC (http://whc.unesco.org). It is also believed that the technology was first used in Northern part of Oman and then in the Southern part (Al-Ghafri et al, 2003). A strong statement is that the population of a single area was dependent on the flow of the nearby falaj system (Shahalam, 2001).

1.4.2 Source

There are three types of sources that can feed a falaj system:

A)Dawudi Falaj-the groundwater type

This type is known in other countries as qanat (Al-Ghafri et al, 2003). Water is derived from a mother well (or multiple wells) located in the mountain mass. From there, sub-surface tunnels (at a maximum depth of 50m) lead the water to the surface. The slope has to be gentle so that the speed is not high and so that erosion is avoided. For ventilation and maintenance purposes shafts are constructed. Furthermore, there are secondary tunnels to ensure that the system has water in case of damage in the main tunnel. Generally, this type requires a lot of initial capital from the construction. Typical width of the canals is 0,5-1m and height 0,5-2m.

B) Aini falaj-the spring type

The system consists of open channels that convey water from a spring to the desert area. The lack of knowledge about the origin of spring water had led people in ancient times to believe that there was an underground ocean. Also, the warm temperature of the water has been linked to therapeutic properties (http://www.omanws.org.om/).

C) Ghaili falaj-the spate irrigation type

Water in this type of falaj derives from wadi beds and shallow groundwater aquifers through infiltration and from rainfall. Moreover, the channels (with length from a few hundred meters to 2 km) are usually open and they do not have water flow all year round. Finally, their height does not exceed 4 meters.

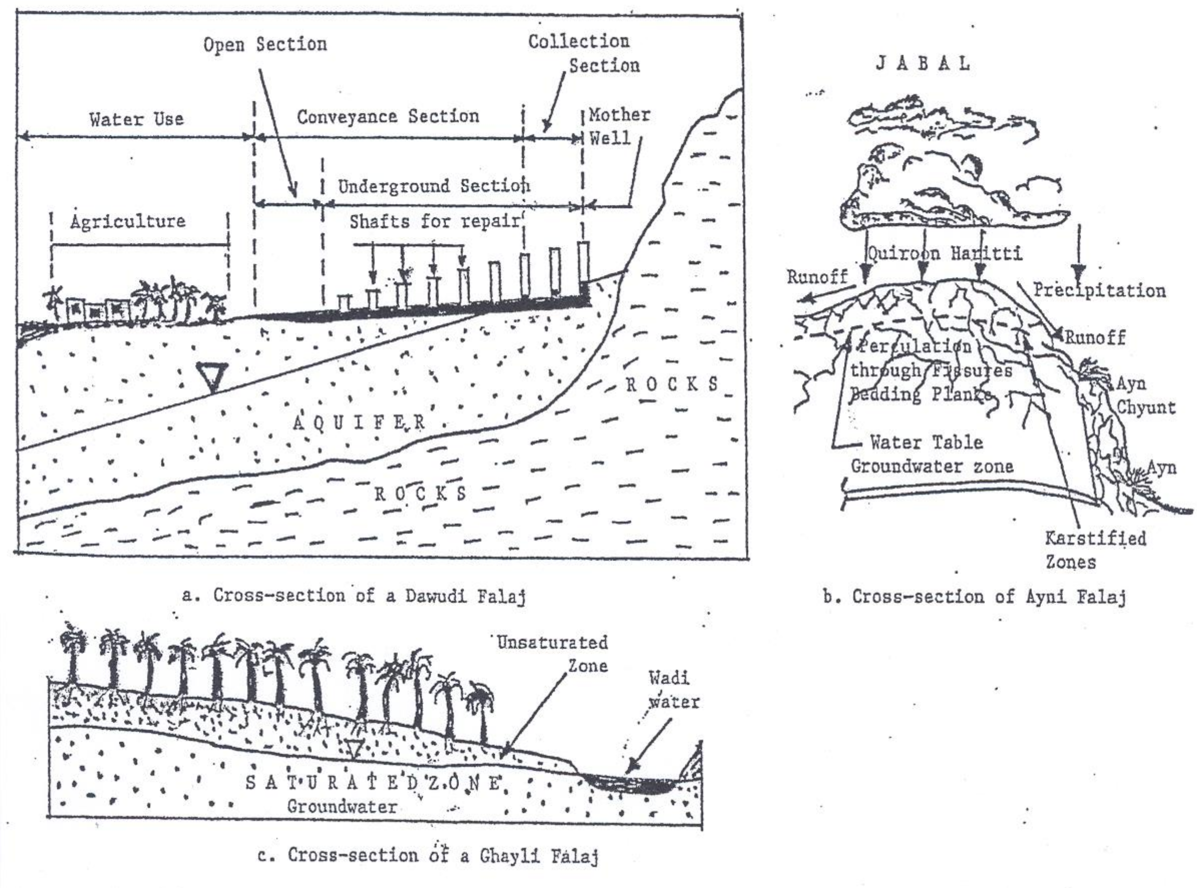


Figure 3. The three types of aflaj systems and their source of water (Source: Shahalam, 2000).

There are several types of aquifers that are known to supply the aflaj systems with water (http://www.unep.or.jp):

- Alluvial Aquifers in Wadis (renewable source, with limited fluctuating flows)
- Alluvial Fans Aquifers (limited flow with high velocity)
- Alluvial Plains Aquifers (high and stable flow, characteristic of the Al-Batinah region)
- Regional Aquifers (stable flow for long periods); Local Flow Systems (flow in Wadi channel), Intermediate groundwater flow systems (often discharged into the sea), Regional Aquifer Systems (large volumes from mountains to desert)

In dry months water is reduced by 50% and in dry years the reduction can be at the scale of 90%. Flow derived from intermediate groundwater flow systems is more resistant to change.

1.4.3 Distribution

In a video made by Unesco (http://whc.unesco.org/en/list/1207/video) about present falaj systems it is stated that water in the falaj systems is enough for irrigation but not enough to perform parallel irrigation of all canals. From the snapshots of the video and from photographs in the same site (http://whc.unesco.org/en/list/1207/gallery/), we can observe that in order to irrigate the fields, there are openings in the canal system,operated with sluices. Sluices and stones are also used to isolate water so that it flows in specific parts of the system at a time. Figures 4 and 5 show the use of stone instead of sluices and the flow from an outlet to a field.

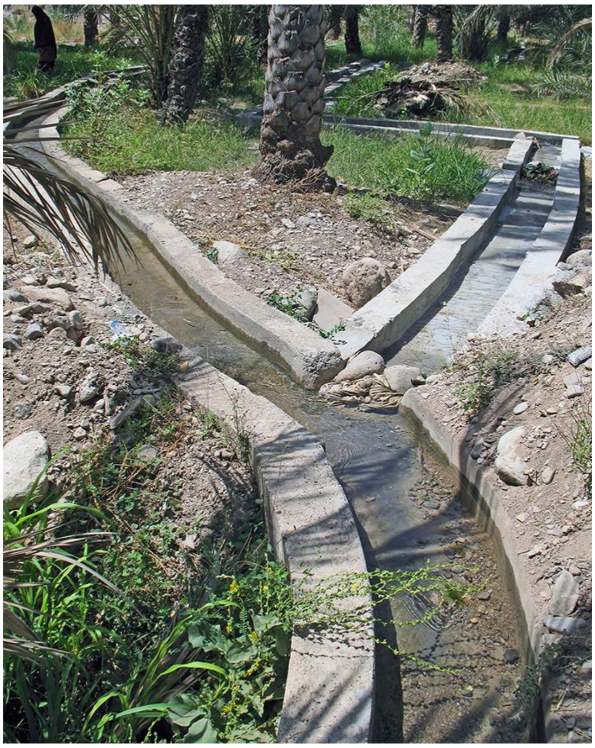


Figure 4. Diversion of water with stones in modern falaj system. (Source: yade.edu)

Figure 5. Outlet in a falaj system in Oman (www.landolia.com).

The traditional priority in water distribution is shown in Figures 6 and 7. It is important to note that agriculture comes last in priority and also that date palms are irrigated before seasonal crops.

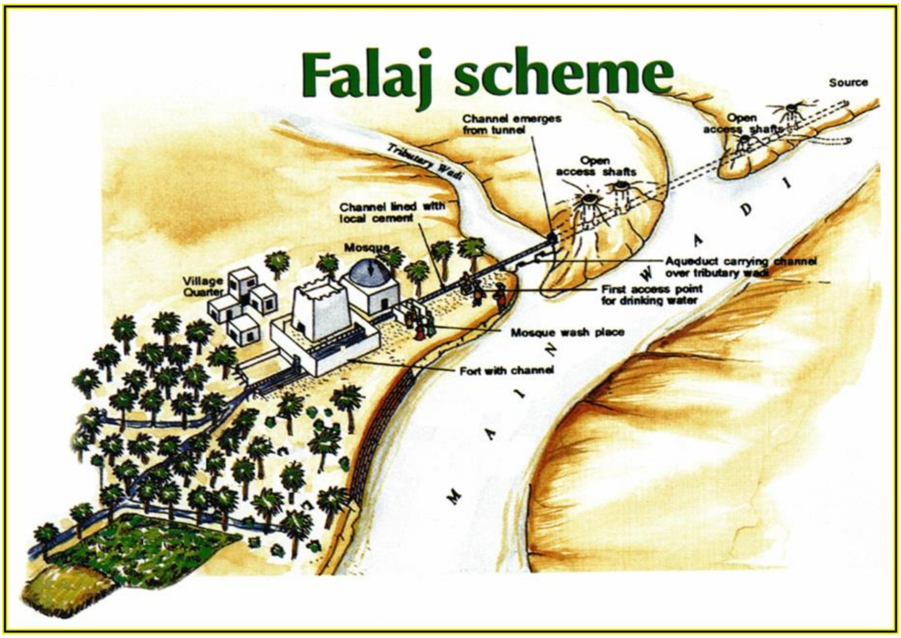


Figure 6. Irrigation distribution (http://www.4gress.com).

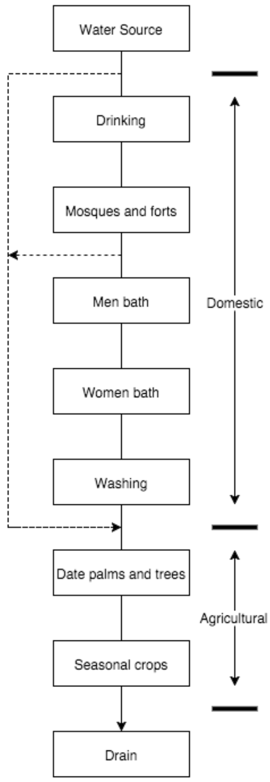


Figure 7. Priority of use in aflaj systems (Source: Al-Ghafri, 2003)

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1.4.4 Water shares and allocation

The users of the falaj can own/rent land and/or own/rent water shares. Some water shares are owned by the community and are rented so that the community has money for maintenance and public works. The private water shares are considered property and can be inherited or even sold to users from downstream water systems. The shares are allocated based on time (http://inweh.unu.edu/). Time management has been possible with the help of the sun in the days and of the stars in the nights. A day is divided into 2 bada and each bada into smaller units with the smallest one corresponding to less than a second. The one bada corresponds to the duration of the night and the other to the duration of the day. This method caused difficulty in the past because of the seasonal differences between duration of the day and the night. An alternative method is the use of a cylindrical object full of water and inside another object with specified volume and a small hole on the bottom for the water to pass through. One water share is the time needed for the water to fill the smaller object.

Irrigation rotation is dependent on the soil and the flow in the system, varying from 4 to 20 days. When there is a dry spell, irrigation rotation is altered so that all the flow is exploited. Time corresponded to water shares is changed analogically and this is one of the advantages of using time versus volume to define the shares. On the other hand, domestic use of water is free of charge. Water is taken in a location that is upstream of the fields (Zekri and Al-Marshudi, 2008) and thus water flow in the fields may fluctuate.

1.4.5 Falaj administration

Figure 8 shows the hierarchical order for falaj administration. The roles of the administration are (Al-Ghafri, 2003):

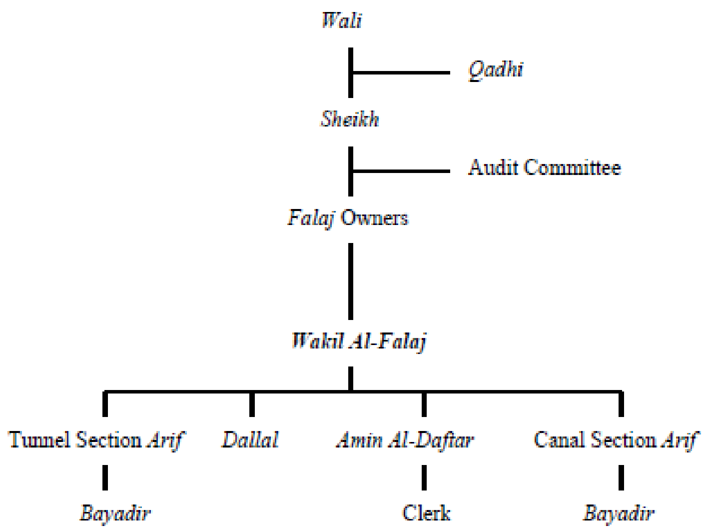

Figure 8. Falaj administration, (Source: Al-Ghafri, 2003)

- Governor (Wali)
- Qadhi (Judge): Resolution of lasting conflicts using the Islamic law.
- Head of the village (Sheikh)
- Audit committee: Composed of village members and responsible for checking the cash flow books of the falaj.
- Administrator (Wakil): Responsible for water shares, economic management of the falaj, conflict management and general decision maker. The head of the villages and the falaj owners assign him. If the falaj is relatively small the only management stuff is the administrator.
- Assistants (Arif): Responsible for timing irrigation.
- Banker (Amin Al-Daftar): Similar duties to an accountant.
- Auctioneer (Dallal): Responsible for renting the water shares and organizing the events for the auctions.
- Labor (Bayadir)

1.5 Specific research goals:

- Understand the function of the system.
- Understand the limits, in terms of management, which are inherent to the system.
- Gain insights about the human actions the system required to function.
- Gain insights about the evolution of the system.
- Gain insights about priorities in the fields.
- Check if there could be possible conflict among the users of the system or with the downstream field systems.

1.6 Chapters' overview:

Chapter 2 focuses on the description of the system.

In chapter 3, the methodology is analyzed.

In chapter 4, the conceptual modeling is discussed.

In chapter 5, results from a raw data analysis are presented.

In chapter 6, the modeling process is analyzed, the scenarios used are explained and the numerical results are shown along with brief remarks.

In chapter 7, the results are elaborated in order to provide insights about the system regarding its social aspects.

Chapter 8 gives an overview of the general conclusions drawn from the research and suggestions for future research.

2. Description of the system

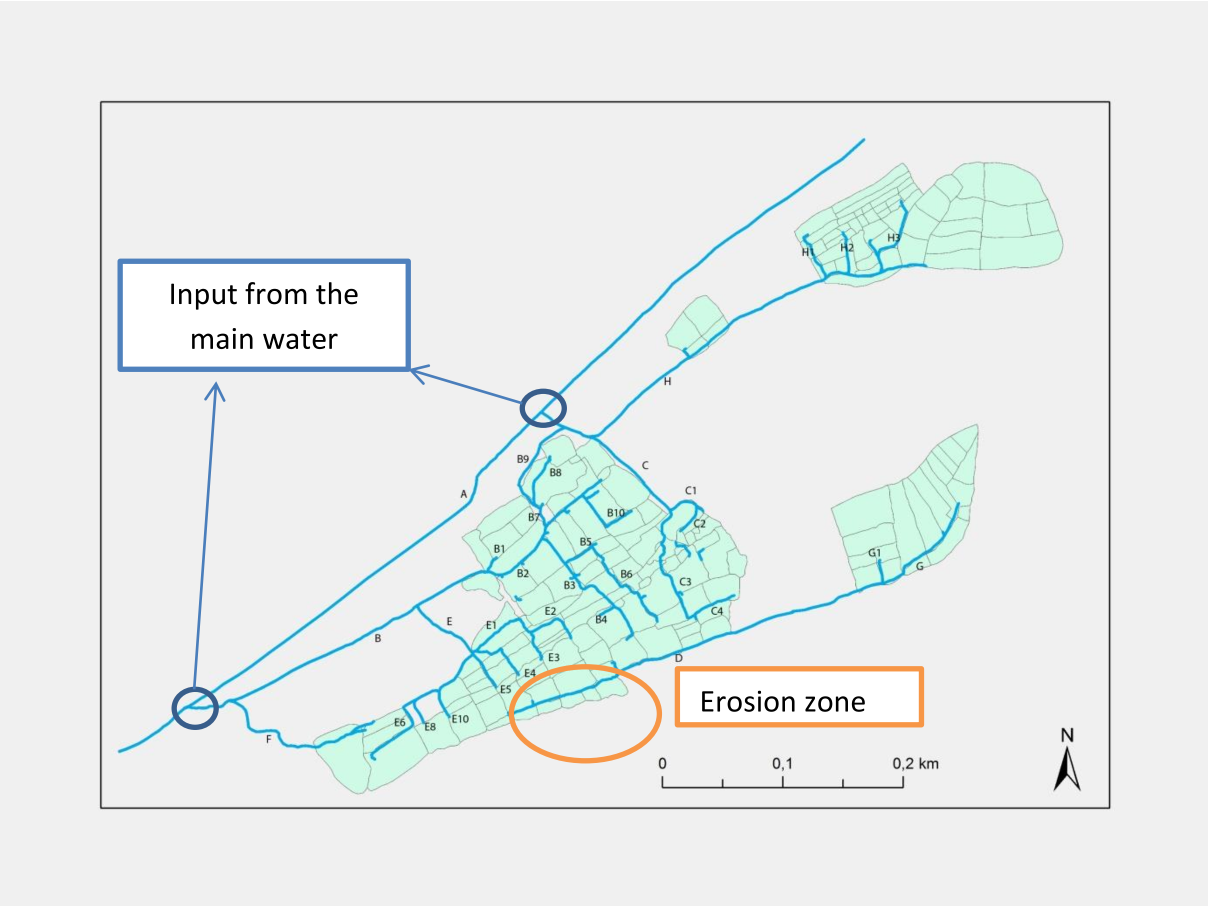

Figure 9: The studied irrigation system. Water flows with gravity.

2.1 Canal system

The water enters the irrigation system from the main water system (Falah al Mutaridh) in two intakes as indicated in Figure 9. The main water system is symbolized as canal system A. The distribution of water is served by canal systems symbolized as B,C,D,E,F,G and H. Canal system D could have served as drainage. It is also connected with canal systems E and G. It is interesting to note that in the start of canal system D the field area is eroded. Figure 10 shows the erosion zone.

Figure 10. Erosion zone (Photo from Wadi Al Jizzi Expendition 2014).

Canal system A is made of stone and is well preserved (Figure 11). Canal systems F and D (Figure 12) are made of stone cement and they are both well preserved. In the other canal systems the canal bed is not well preserved and rocks form the canals on both sides.

Figure 11.Channel A (Photo from Wadi Al Jizzi Expendition 2014).

Figure 12. Channel D (Photo from Wadi Al Jizzi Expedition 2014).

2.3 Fields

The total area of the 180 fields is 68,082 m^2. The fields have stone boundaries between them (Figure 13). Some of them are terraced (Figure 14). Also, walls surround some of the fields (Figure 15). Finally some fields have circular stone bunds (Figure 16) that probably accommodated date palm trees.

Figure 13. Stone boundaries in fields (Photo from Wadi Al Jizzi Expedition 2014).

Figure 14. Terraces in fields (Photo from Wadi Al Jizzi Expedition 2014).

Figure 15. High walls in fields (Photo from Wadi Al Jizzi Expedition 2014).

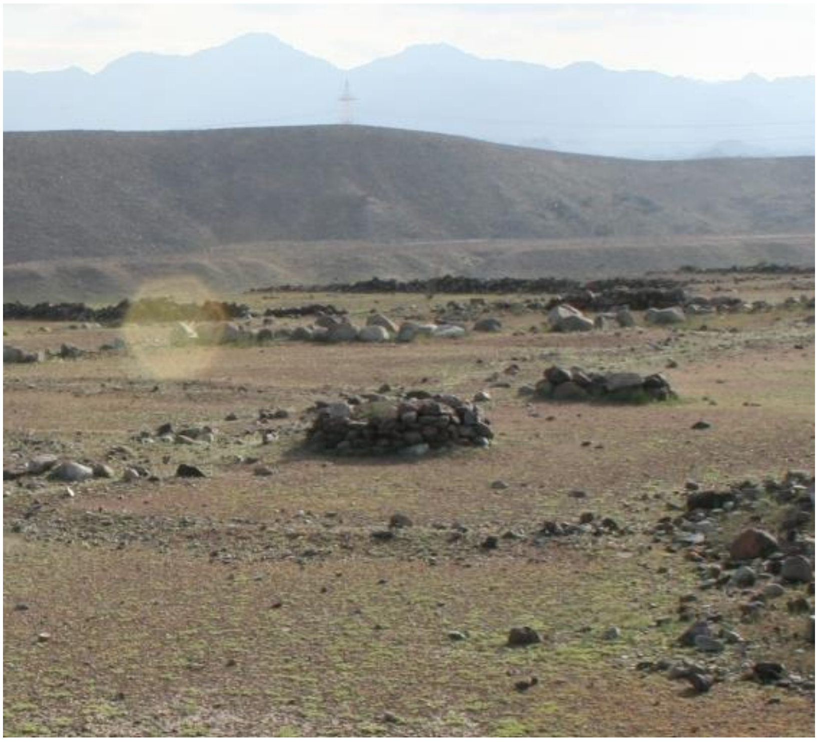

Figure 16. Circular bunds in fields. Photo from Wadi Al Jizzi Expedition 2014.

2.4 General Water system

2.4.1 Source

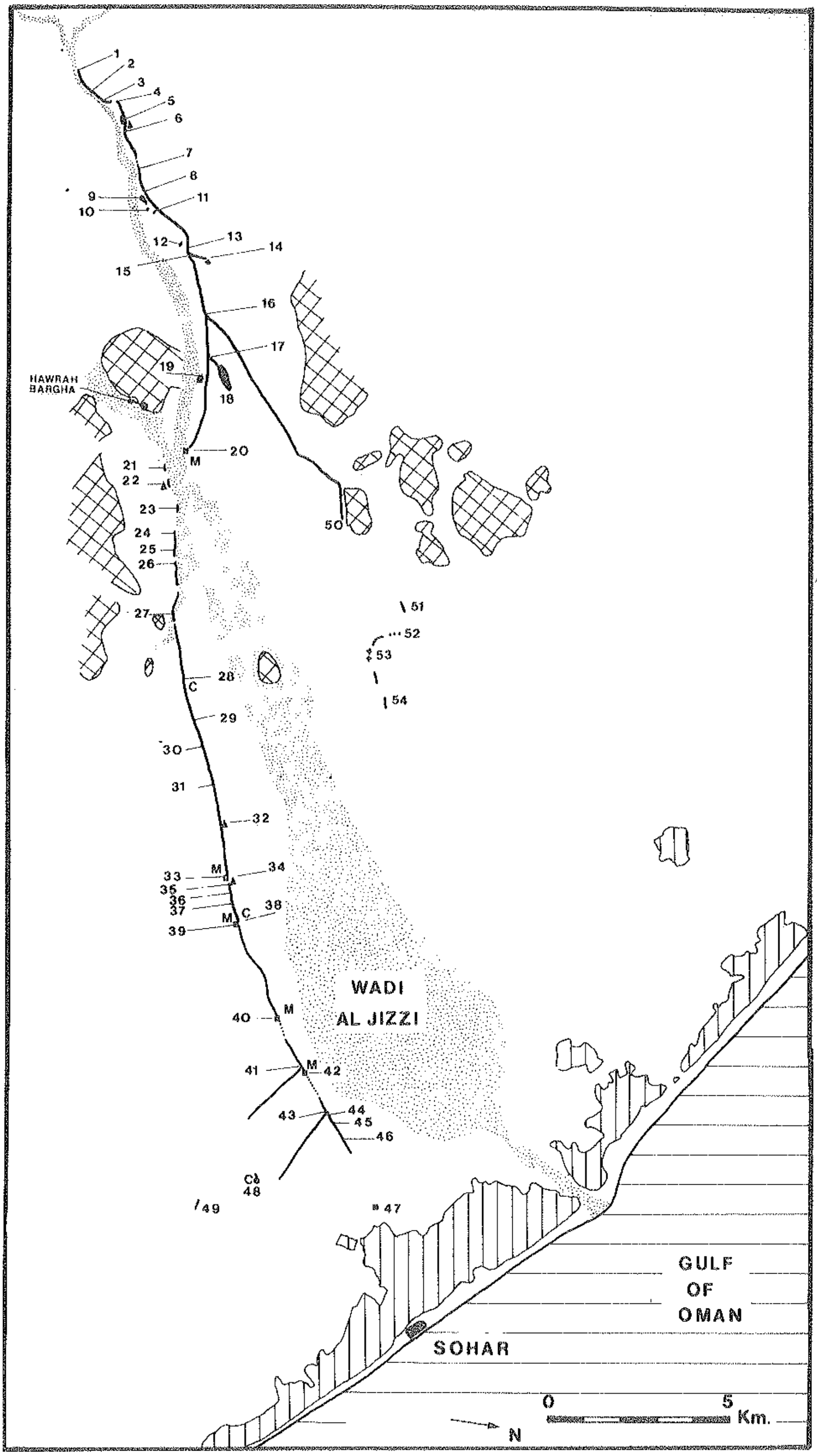

Figure 17. Main water system and parts (Source: Costa and Wilkinson, 1987).

The source of the system is yet unknown. Costa and Wilkinson have commented that the water system that nearby water systems are fed from a natural pool. During the field study of 2014, a natural pool was found in the most upstream part that was reachable. This pool could have served as the source of the main water system. Another possible water source is the qanat system that was found near the pool.

2.4.2 Other field systems

By the time the fields were used (16^{th} -17^{th} century) only the upper part of the falaj was active. The irrigation system of focus consists of the fields at points 9-10-11 shown in Figure 17. Some remarks about the map of Figure 17:

- Fields at point 3. Costa and Wilkinson (1987) mention that the fields belong to a Ya'riba or a post Ya'riba settlement and were used until recently.
- Fields at point 5. The book mentions that they were recently abandoned but does not mention the period they were constructed.
- Fields at point 12. No mention about the time they were first used or abandoned.
- Fields at point 13. The book mentions that the fields belonged to Sihlat but there is no other mention about the period of use.
- Fields at point 18. The book mentions that they were first used in the 9th-10th century. No date of abandonment mentioned.
- Fields near Sohar (possibly from the 9th-10th century).

From the previous historical reference and the new archaeological updates it is safe to assume that at least the fields at number 12 and the fields of the Sihlat settlement were used simultaneously with the fields of focus. This means that there was a shared interest for the water of the falaj. This may have been a major source of conflict between the neighboring settlements.

2.5 Flows

Due to the rock collisions along the water system, there are uncertainties regarding the flows in the system. Also, no written records concerning the flows have been found.

2.6 Settlement

On some parts of the irrigation system, buildings were found that probably belonged to the settlement that was using the system (Figure 18). None of these buildings has been identified yet as a mosque, which means that we cannot be sure that the traditional agricultural practices were being performed.

Figure 18. Water system and settlement location.

3. Methodology

Two kinds of analysis are performed: the raw data analysis and the modeling analysis. In the former, the elevation data are analyzed in combination to the location of the fields and the canal systems. Then we identify the fields that are irrigated by the same canal system and the fields that are irrigated by field to field irrigation. The fact that the irrigation system functions with gravity does not mean that all canal systems were constructed to enable flow to the fields they feed. There is also a possibility that canals coexist with other canals that could potentially serve the same part of the system. A final goal of the raw data analysis is to identify these fields.

Concerning the analysis that includes the simulation with the hydraulic software we know that water systems are built to bridge the gap between water supply and demand. Figure 19 shows the scheme for this irrigation system. For our case, we know nothing about the input of water and the water demand. This is why the methodology is based on the hydraulic properties and scenarios are made for the unknown variables.

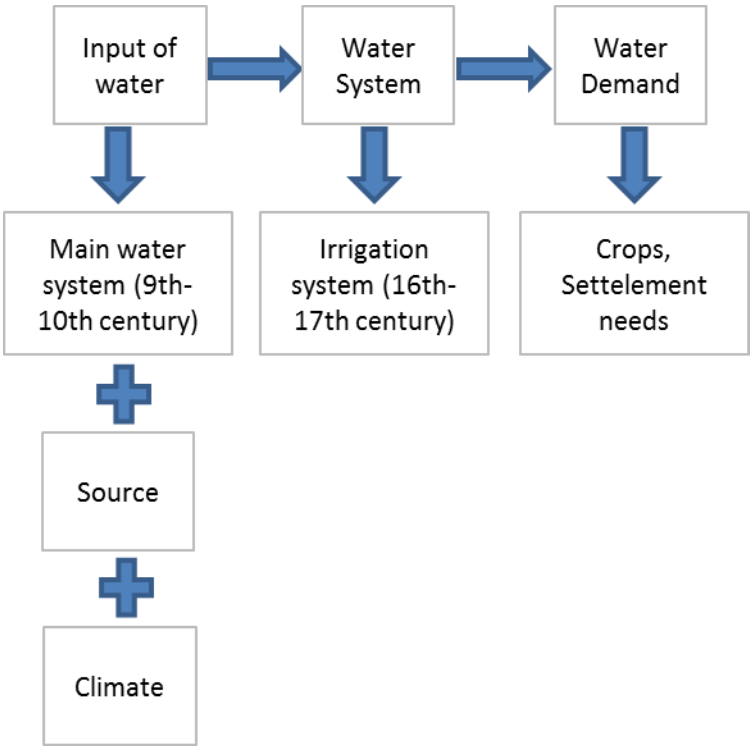

Figure 19. General Scheme of the Water Balance in the System.

3.1 Input of water

The water that is derived from a source located inside the mountain mass enters the irrigation system through the main system (Figure 19). Presently, even in the winter months there is no flow in the main canal or in the irrigation system. This leads to uncertainty regarding the past flows and the scale of the volumes that entered the system. The amount of water is dependent on the following factors:

- Availability of water. The availability of water is dictated by the climatic conditions of the area. The present climate in the Sohar region, in which the system is located, is classified as hot desert climate (Wikipedia.og) and the annual rainfall is approximately 108mm. The construction of the main water system, where the input comes from, is estimated to be 1000 years old. From the historical sources it can be implied that the area back then was arid. The proxy data that refer to Oman and the Arabian Peninsula (Cook et al, 2010, Anderson et al, 2002, Lückge et al, 2001, Fleitmann et al, 2003) and Northern Oman (Burns et al, 1998) are not detailed enough for the studied period. Thus, it is safer to use the present climatic data.
- Source of water system: The type of source (flood water, groundwater, spring or surface water) is not known. Other falaj systems in Oman are known to be supplied by stable spring water (Nagieb et al,2004)
- Structural limits: The input in the system is limited by the dimension of the main canal in the point of the input. The cross-section that is well preserved is rectangular and has dimensions of 0,97m height and 0,58m width.

3.1.1 Scenarios for water supply

From the 3 parameters mentioned above, it becomes apparent that the best approach is to explore the structural limits. Thus, in order to address the uncertainty of the unknown input flows, two scenarios (Table 2) are created based on the water level at the point of the known cross-section.

Table 1. Scenarios about the input flows.

	Scenario		Level from canal bed (m)	Initial water level (m)
1	20%	of max water level	0,194	205,894
2	80%	of max water level	0,776	206,476

3.2 Water demand

The water demand that this system was built to satisfy can be divided into the irrigation demand and the settlement demand. Apart from irrigation, there hasn't been any evidence that the water was indeed used for the settlement. Settlement demand will be considered in the analysis process, because no other means of water supply for the inhabitants were found in the field study, but will not be modeled.

The irrigation demand is dependent on:

- The crops
- The regional climate
- The agricultural practice
- The soil

The crops and the climatic data dictate the crop needs in relation to the yields. The type of the source of the systems limits the agricultural practice. For example, if the source of the system is flood water then the system would only irrigate the fields after flood events, which happens very few times in Oman. Finally, if there is no limitation posed by water availability, the irrigation intervals depend on the soil.

We cannot be sure about the type of crops grown in the fields. From literature, it is apparent that the date palms played a really important role in everyday life in the past centuries (Dutton et al,1999). In this field system, at least in some fields, there are other crops. For example, similar circular stone structures as those found in the fields, have been used in fields today to accommodate date palms in one field, probably for the provision of shadow. Therefore, in the fields with the circular structures, the crops that were grown must have been other than date palms. Another observation about the system concerns the terraced areas. The terraced areas are currently used to give priority to the crops derived from trees so that they have secured their water supply (Britannica.com). If this practice were used in this system, it would imply that in the different levels of the terraced areas different crops were grown. Some crop types that are popular in Omani agriculture are sorghum, barley, mangoes, fruit trees, wheat and alfa-alfa (Britannica.com). Other indications about the type of crops grown in the fields do not exist. It could be assumed that the settlement would desire enough food in order to survive but this cannot be proven in this stage.

In a recent study that was carried out in a field system in Northern Oman the water needs were calculated for wheat and date palms (Norman et al, 1997). Today's wheat is different from the past one. The crops need more water (Zhu et al, 2015). Also, the climatic data might be different. Due to lack of evidence, error could occur in calculating the past climatic data and the water needs of the past crops. As a result, we use only the present climatic data and the water needs from this study (Table 2). Also, for simplification purposes, it is assumed that all the fields contain wheat. Modern wheat has higher water needs than past wheat but lower than date palms. This is why it serves as an average scenario for water demand.

Table 2 shows the water needs from the study. The water needs in the study were used for a specific interval. The interval is dependent mostly on the soil and secondly on practical aspects of irrigation. More field capacity means larger intervals. Table 3 shows the water needs adjusted for different intervals. The calculations have not taken into consideration the evaporation in the fields.

Table 2..Water needs for wheat and date palms and calculation of averages (Source: Norman et al, 1997).

Plot		Field 1	Field 2	Field 3	Field 4	Field 1	Field 2
Crop		wheat	wheat	wheat	wheat	dates	dates
Area	(m2)	419	520	365	249	465	299
ETmax	(mm)	344	358	411	377	1940	1943
ETa	(mm)	305	332	358	345	1779	1611
S	(mm)	41	29	23	17	44	52
Pe	(mm)	48	28	24	10	262	337
IRR	(mm)	272	333	406	531	1882	1245
Yields	(T/ha)	3.7	3.7	4.3	3.9	25	29
Start day		4/11/1995	9/11/1995	29/10/1995	5/11/1995	31/10/1995	6/10/1995
Finish day		23/2/1996	7/3/1996	8/3/1996	5/3/1996	26/10/1996	1/10/1996
Days		111	119	131	121	361	361
Total amout		216	275	311	318	1473	1222
mm/d		1,95	2,31	2,37	2,63	4,08	3,39
Average mm per day		2,31				3,73	

Table 3. Average water needs for different irrigation intervals.

Irrigation interval	Wheat (mm)
1	2
2	5
3	7
4	9
5	12
6	14
7	16
8	19
9	21
10	23
11	25
12	28
13	30
14	32
15	35
16	37
17	39
18	42
19	44
20	46

3.2.1 Soil

The type of the soil in the fields is not known. The photo (Figure 20) shows that the top layer is gravel. The soil in the general area of study is considered to be relatively fertile which corresponds to loamy soils (FAOa). This is reinforced by observations of the area after rain events. Therefore, the soil does not behave as clay or sand. The soil plays an important role in the irrigation. It influences the irrigation intervals, the flow in the fields, especially for field to field irrigation, and the water losses in the canals. Numerically, the soil type is reflected in the infiltration rate.

Figure 20. Photograph from ditch in the canal system B. Photo from Wadi Al Jizzi Expedition 2014.

The infiltration in a specific moment for a specific soil is dependent on various factors. On a semi-arid area where the groundwater table is low, the rate is mostly dependent on the amount of water the soil receives and the duration of the rain/irrigation. At first the infiltration is really high and then it lowers to the saturation rate. Using the Green Ampt method, a sensitivity analysis was performed in order to understand the scale of error that could be made by using a specific infiltration rate. The method uses the parameters of loam and then for a specific amount of water supply and time of irrigation, it calculates the average infiltration rate.

Tables 4,5 and 6 show the results of the sensitivity analysis of the infiltration rate when we change the irrigation amount and the duration of infiltration. Column 1 in each table shows the total hours of irrigation. Column 2 shows the result of the Green Ampt calculations with Matlab and Column 3 shows the hourly amount we give to the fields based on the total amount and the total duration of irrigation. Each table corresponds to a different total amount; table 4 uses total amount 33,375mm, table 5 uses 50 mm and table 6 uses 75mm total per day. All tables refer to loam.

Table 4. Sensitivity analysis for different irrigation durations (Total amount: 33,375mm, Soil:Loam)

Duration of irrigation	Mean infiltration (mm/h)	mm/h	St dev	% (stdev/average)
1	5,429	33,375	0,019710403	4%
2	5,236	16,6875	Total irrigation amount (in mm)	
3	5,127	11,125		
4	5,05	8,34375	33,375	
5	4,992	6,675		
6	4,944	5,5625		
7	4,903	4,767857		
8	4,868	4,171875		
9	4,835	3,708333		
10	4,806	3,3375		
Average	5,019			

Table 5. Sensitivity analysis for different irrigation durations (Total amount: 50mm, Soil: Loam)

Duration of irrigation	Mean infiltration (mm/h)	mm/h	Stdev	% (stdev/average)
1	4,9	50	0,013382082	3%
2	4,765	25	Total irrigation amount (in mm)	
3	4,69	16,66667		
4	4,638	12,5	50	
5	4,599	10		
6	4,567	8,333333		
7	4,54	7,142857		
8	4,516	6,25		
9	4,495	5,555556		
10	4,477	5		
	4,6187			

Table 6. Sensitivity analysis for different irrigation durations (Total amount: 50mm, Soil: Loam)

Duration of irrigation	Mean infiltration (mm/h)	mm/h	Stdev	% (stdev/average)
1	4,51	75	0,009434	2%
2	4,406	37,5	Total irrigation amount (in mm)	
3	4,353	25		
4	4,318	18,75	75	
5	4,291	15		
6	4,269	12,5		
7	4,251	10,71429		
8	4,235	9,375		
9	4,222	8,333333		
10	4,209	7,5		
Average	4,3064			

Table 7 shows the results of the sensitivity analysis of the infiltration rate when we change the soil type for specific total amount of irrigation and specific duration of irrigation. The result of the Green Ampt model is shown in Column 2.

Table 7. Sensitivity analysis for different types of soil (Total amount: 33,375mm, Irrigation duration: 4h)

	Mean Infilitration rate mm/h	Distance from average	Duration	Irrigation rate
Clay	0,475	7,5241	4	8,35
Sandy Clay	0,808	7,1911		
Silty Clay	0,968	7,0311		
Clay Loam	1,246	6,7531		
Silty Clay Loam	1,986	6,0131		
Sandy Clay Loam	2,527	5,4721		
Loam	5,05	2,9491		
Silt Loam	12,244	4,2449		
Sandy Loam	16,706	8,7069		
Loamy Sandy	37,981	29,9819		
Silt	-			
Sand	too high			
Mean	7,9991	2,9491		

The sensitivity analysis shows that the selection of type of soil is important but the irrigation amounts and the duration of the irrigation are not as significant as the type in comparison. The infiltration rate chosen for the fields is the slit's loam average rate that was calculated as 12,4mm/h for 4 hours of irrigation and rate of 8,35mm/h. This corresponds more or less to the saturation rate of sandy loam in the literature (Van Genuchten et al, 1991). During the irrigation event, the fields receive the water in a limited amount of time. The saturation rate is representative because it is reached really quickly and also for simplification purposes it serves as a safe choice.

Errors in the infiltration rate mostly affect the supply of water to downstream fields that are irrigated from previous fields and not directly from the canals. This is because in order to have run off from a field the input rate must exceed the infiltration rate and there must be a thin layer of water in the field. This can create a false perception of the irrigation duration. The results are amplified if the flow is too high.

3.2.2 Scenario for water demand

The scenario for the water demand was formed under the following assumptions:

- The soil is fertile and behaves as some type of loam.
- The water needs as described in the Northern Oman study, are satisfied with regular irrigation throughout the wheat period.
- The irrigation interval is 10 days.

The above lead to irrigation needs 23,15mm every 10 days.

3.3 Water system

3.3.1 Irrigation method

There are three general types of irrigation in terms of field priority:

A. Simultaneous irrigation of all fields
B. Irrigating firstly the upstream fields and afterwards the downstream ones
C. Irrigating firstly the downstream fields and afterwards the upstream ones

In order to achieve type B and C, hydraulic structures are needed to control the flow. In the case of type B, after the irrigation completion in the upstream fields flow must be diverted to the downstream ones. The opposite happens to the type irrigation type C. In the studied system, the archaeologists found stones in some canal systems. These stones could have been used for the diversion of water. In the modeling, we will use two different methods which correspond to type B. In the first method, flow will run to both the upstream and downstream parts of a canal. After the upstream fields have been sufficiently irrigated they will be closed with stones. Then, when all the fields of a canal have been irrigated, stones will be placed in the canal to stop the flow. In the second method fields will be grouped from the upstream part of a canal or a canal system to the downstream. The canal will be closed in the downstream end with a stone so that no other field will get water. When the irrigation has been completed the stone will be removed and will be put on the downstream end of the next fields.

3.3.2 Structures in the system

The system is comprised of the canal systems, the borders of the fields, the walls, the fields (terraced or not), the circular bunds and some buildings belonging to the settlement. Most of them are considered as primary data in the analysis and their existence and dimensions in the past system is not questioned in this study.

3.3.3 Stone settings

The primary purpose of stones-sluices is to divert water so that all the fields can be irrigated and so that the irrigated fields do not flood. The sluices open and close in several places inside the system. The settings are adjusted for each scenario.

3.3.4 Sequence of Fields

Some fields have no access to a canal or an outlet. These fields were probably watered by other fields. Assuming there are two fields in a row, the first field is watered by an outlet or by a canal. When water reaches a specific height which is controlled by the software (1mm), it begins to run-off to the next canal. The sequence is determined by the raw data analysis. If fields are found to be potentially irrigated by two fields, one field is chosen. The criterion for this choice, wherever it can be applied, is the minimization of the number of fields that one field could supply. The sequence of the fields is considered fixed and no changes are made in them during the study.

3.4 Validation of results

In order to consider a scenario realistic for this system, it must support the following:

A) **The system was functional.** The fields must have been sufficiently irrigated. Scenarios in which fields are left without water could correspond to dry periods but not average years.
B) **The system was functional and at least 2 other systems downstream were functional in the same period.** The total irrigation duration of the system must not exceed one third of the total available time of the falaj.
C) Flows must be in accordance with the dimensions of the canals.

Because of the lack of compelling evidence concerning the use of the system, the conclusions refer mostly to excluding scenarios. The remaining scenarios are the ones with the higher probability to have happened. At this point it is very important to highlight that it is not certain that one of the remaining scenarios describes what was really happening. This is because the scenario-making process is limited by the perception of the researchers.

4. Conceptual modeling

An irrigation system is a complex system and only a simplified version can be perceived and modeled. Figure 21 shows the way the system is perceived with the parameters discussed previously:

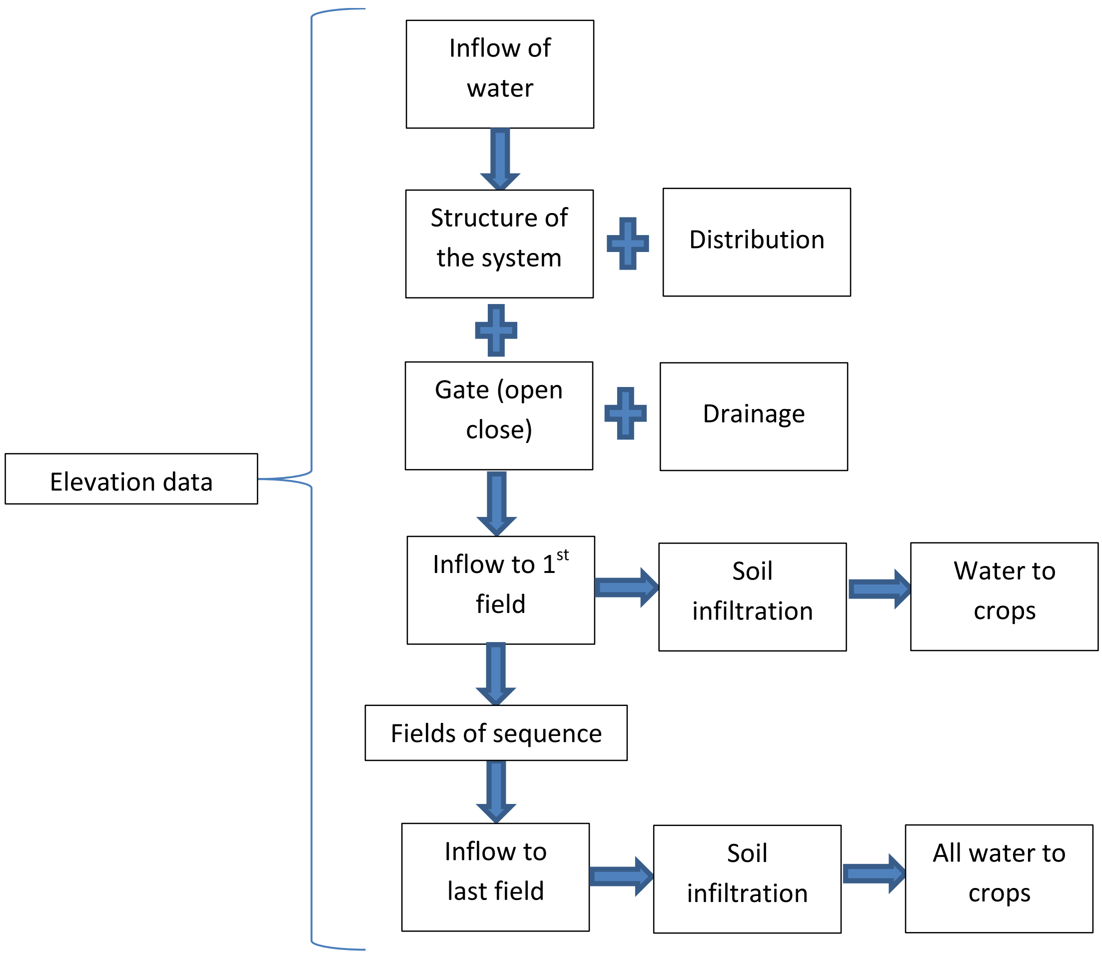

Figure 21. Conceptual modeling of the system's function.

4.1 Parameters excluded from conceptual modeling

The parameters that were perceived but for reasons of cost benefit were not taken into consideration are:

- Loss of water due to infiltration or evaporation
  Evaluation: The size of the system is small enough to assume that there is no water loss (due to evaporation or infiltration) when water is transferred to the fields.
- Changes in the perception of water needs by the farmers
  Evaluation: In this study it is assumed that farmers knew empirically the water needs for a specific yield from the start. Otherwise, the complexity of the simulation would increase unnecessarily. Either way the error concerning the selection of the crops is higher than the error from this approach.
- Sedimentation
  Evaluation: Sedimentation has not been taken into consideration. This assumption was not perceived as risky because in many cases the canal bed could be observed which means that the sedimentation has not been so effective in changing the elevations.

4.2 Synopsis

Table 8 shows the parameters and the number of scenarios for each parameter

Table 8. Parameters in the conceptual modeling and scenarios.

	Scenarios		
Parameters	A	B	C
Inflow of water	20% of max	80% of max	
Distribution	All open	Up to down	Down to up
Structure	Fixed		
Gate settings	Adjusted to each scenario		
Drainage	Implented if needed		
Soil	Sandy loam		
Sequence of fields	Fixed		
Crops	Wheat		
Irrigation intervals	10 days		
Elevation data	Fixed		

4.3 Sobek

For the hydraulic simulation, Sobek 1D was used. Figure 22 shows the modeling scheme in the software.

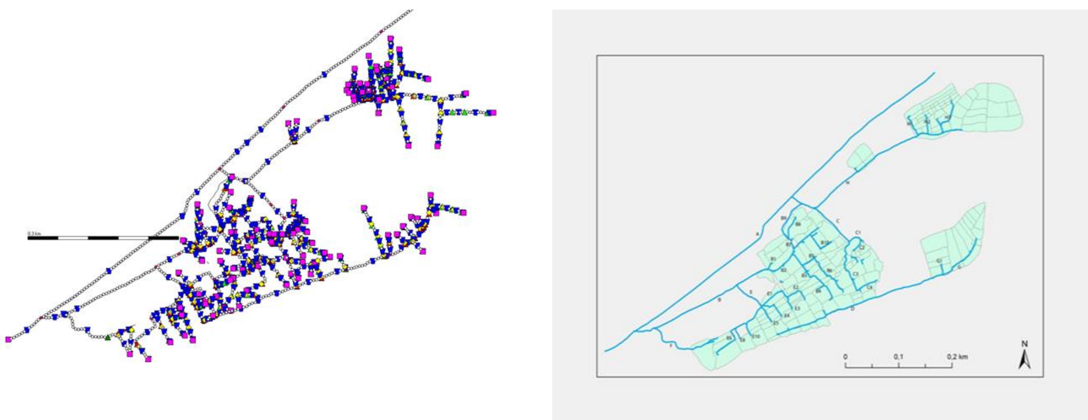

Figure 22. On the left the System in the model and on the right the system from GIS data.

In Sobek the model is further reduced. This is because SOBEK 1D cannot simulate surface flow and overflow. In the model:

- Fields are canals with large dimensions (Figure 23). Irrespectively of the shape of each field, the fields have rectangular cross-section.

$$Width * Length\ of\ canal - field = Area\ of\ the\ field$$
$$Width = Length\ of\ canal - field$$

  The height of the canal-field is 5m so as not to disturb the simulation process. All 180 fields have been simulated separately in order to gain further insights.
  The infiltration of the soil has been inputted as a lateral flow right after the weir of the beginning or the start of the reach. The weir serves as the opening of the field so that water can flow inside. The rate is multiplied by the area of each field, in order to convert it into m^3/s.
- At the end of the last field in the sequence, there are boundary conditions (Figure 23). To simulate the effect of the borders of the fields, weirs with really high elevation have been put at the end of each field to keep the water in.
- Regarding the fields which have outlets, there is no hydraulic structure between the outlet and the field.
- For the fields that are irrigated from the canals without an outlet, it is assumed that a large stone from their borders is removed to let the water from the canal in. The opening of the stone is thought to be about 35cm. This is achieved by putting an artificial outlet of 0,5m and then a weir with a width of 35cm.
- For the fields that are irrigated from other fields, it is assumed that a large stone from their borders is removed to let the water from the other field in. As in the previous case the opening is 35cm.
- The elevation data are inserted in the cross-sections. For most of the fields there is one cross-section definition and thus one elevation data. When the field is located in a strategic point there is one extra cross-section definition in order to make the elevation transformation smoother. In the canal systems there are at least two cross-section definitions at each reach. The elevation at each definition is calculated with interpolation between the two cross-sections but also between the reaches.
- Most of the canals are of rectangular cross-section, which is considered to be a closed canal in Sobek. In order to simulate them as open canals, the height in the cross-section definition has been set to 5m.
- When three branches intersect, there can be linear interpolation in only two of them. This affects the continuity of the elevation and the slope in some braches.
- Generally, water is retained in the fields due to the borders of the fields. In some cases there are high walls surrounding one or a group of fields. The effect was not modeled.

- If the water level exceeds the maximum water level, Sobek will not make alterations to keep the flows realistic. This means that when high flows occur in the system, they will reach the fields instead of overflowing in the canals.

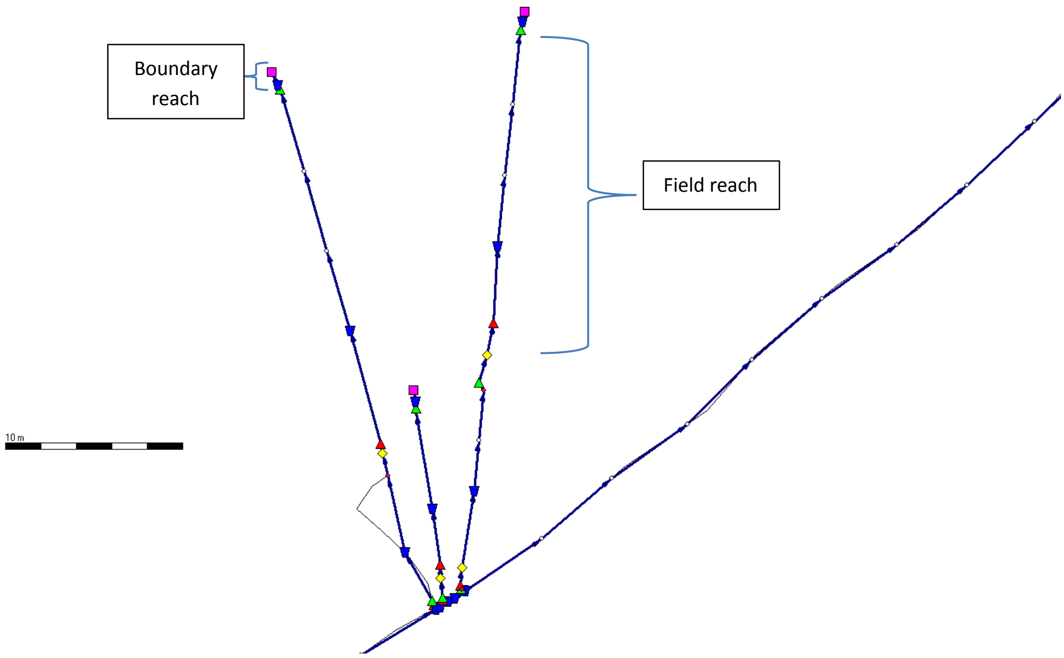

Figure 23. Boundary and Field reach in the Sobek model.

4.3.1 Determination of irrigation completion

The irrigation completion for each field is determined with the water balance method.

- For the first part of each field the time series of discharge is documented and marked as Q_{in}. The positive values mean that water enters the field.
- If the field is not connected to other fields on the downstream side then no other documentation is needed. If the field has other fields on the downstream side then the time series of discharge in the first part of the other field is also documented and marked as Q_{out}.
- When there is a sequence of fields the irrigation duration is calculated firstly for the most downstream field.
- The water needed for each field is 23,15mm. The irrigation duration is time t when:

$$Water\ layer(t) = \frac{Qin(t)}{area} + Water\ layer(t-1) = 23{,}15mm + \frac{\sum_{i=0}^{i=n} Qout(i)}{area}$$

  Where n is the irrigation duration of the field which is located right downstream. If n<t then the gate which is put into the field downstream closes at n. If t<n then a gate cannot be put in the field before time n to ensure sufficient water flow in the downstream system.

The stones in the fields are simulated as weirs which rise enough after the irrigation completion to prevent water from flowing.

5. Raw Data Analysis

5.2 Elevation data

Could the construction of canal system F have been prevented by constructing E first?

The elevation lowers from F to E in the upper fields and from north to south. Figure 24 shows that Field 2 has the same elevation as field 3 but higher elevation than field 4 so flooded water would preferably go to field 4. Water cannot flow either from field 1 to 5 due to the slope or from field 3 to field 5 due to the higher upper parts. This makes the canal system F essential for the irrigation of fields 1 and 5..

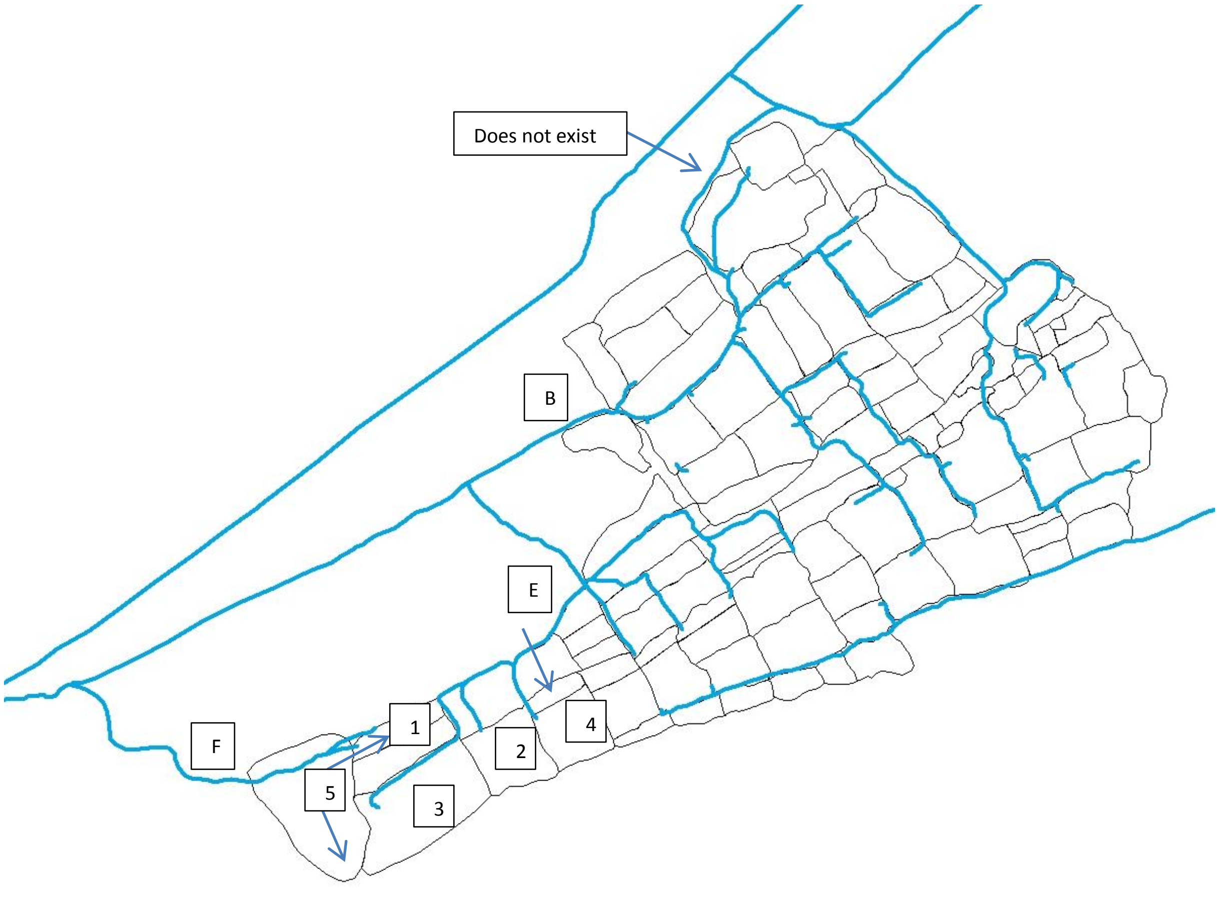

Figure 24. Canal system F and E in Raw Data Analysis.

Could canal system E have been the extension of channel B?

According to the slopes (arrows in Figure 26 point to low elevations) channel C could have been an extension of B. One possible explanation is that the fields supported by the canal system C were built afterwards and the dimensions of the sub canals did not suffice to supply the fields in C.

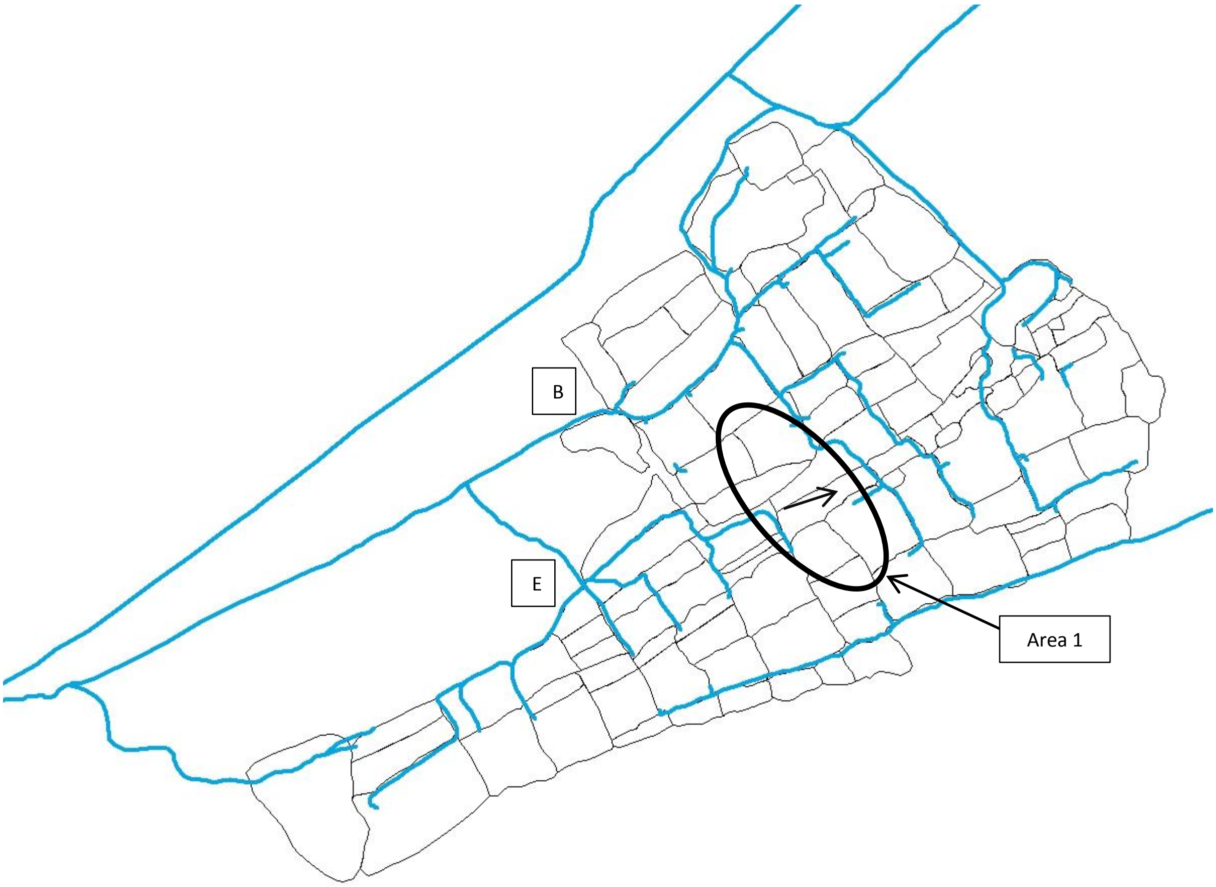

Figure 25. Canal system B and E in Raw Data Analysis.

Could Channel C have been an extension of channel B?

According to the slopes (arrows in Figure 26 point to low elevations) channel C could have been an extension of B. One possible explanation is that the fields supported by the canal system C were built afterwards and the dimensions of the sub canals did not suffice to supply the fields in C.

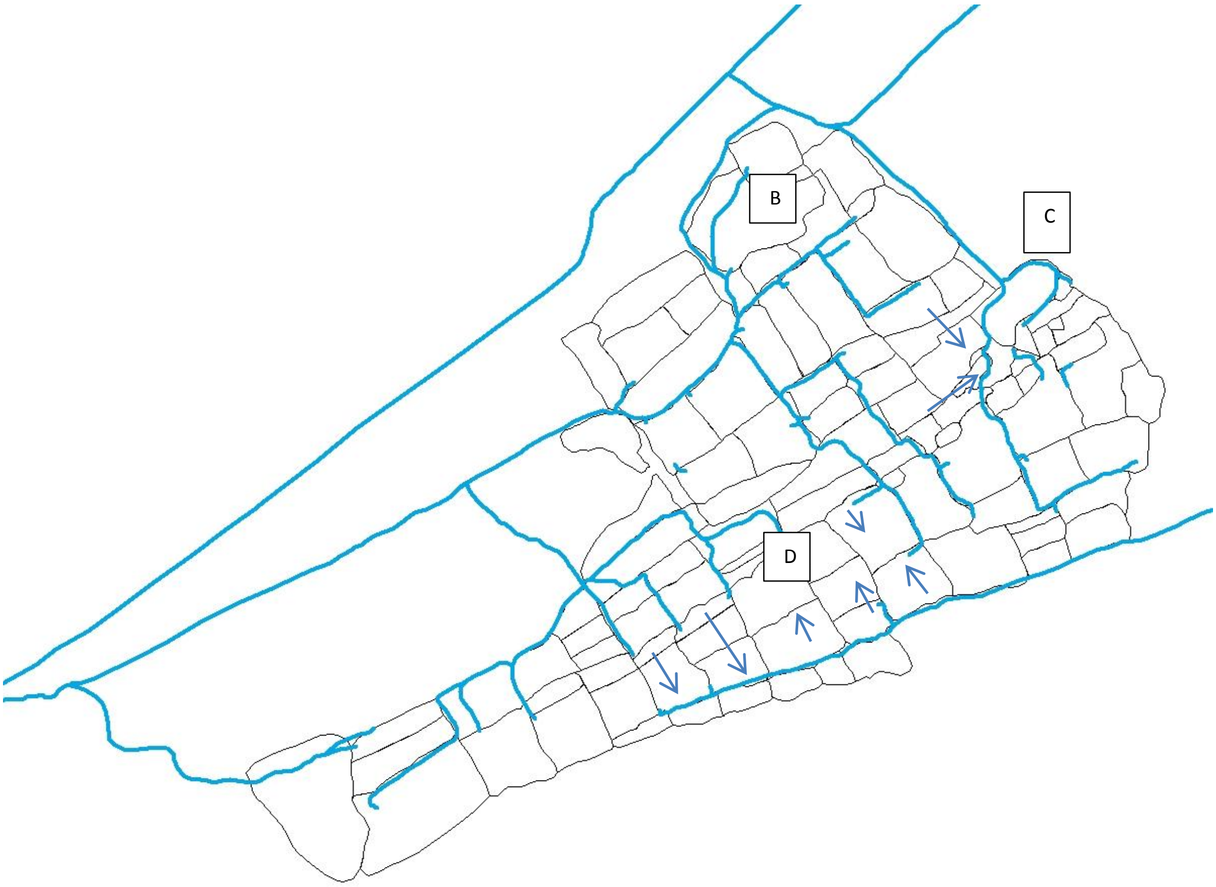

Figure 26. . Canal system B, D and E in Raw Data Analysis.

What is the function of channel D?

Channel D supplies water to the isolated field subsystem and to some southern fields of the main system. Canal D could have been connected to canals E4 and E5 even if a connection has not been found (Figure 26). Elevation data show that this is the only way that canal system D could get water from intake 1 or 2. In all other cases topography does not favor the flow to the system.

5.2 Canal systems and fields.

From the raw data analysis each field was linked to one canal system. From this match, the areas that each canal system irrigates were calculated (Table 9).

Table 9. Canal systems and areas they supply.

System	Area in m^2	Percentage
H	17418	26%
F	2512	4%
D_G	11688	17%
E	10277	15%
C	5275	8%
B	19577	29%
other	1335	2%
all	68082	100%

6. Experimentation with the System

6.1 Intake 1 and 2

Simulations were performed to understand the hydraulic connection between intake 1 and 2. The results show that if we close the first intake, the second intake gets more water for the same flow in the general system. On the other hand, if we close intake 2 there is no change in the flow of intake 1 (Figure 1).

Remarks from results: There is a power relation between intake 1 and 2. Users of the irrigated fields by intake 1 have more power over users of the irrigated fields by intake 2 than the opposite.

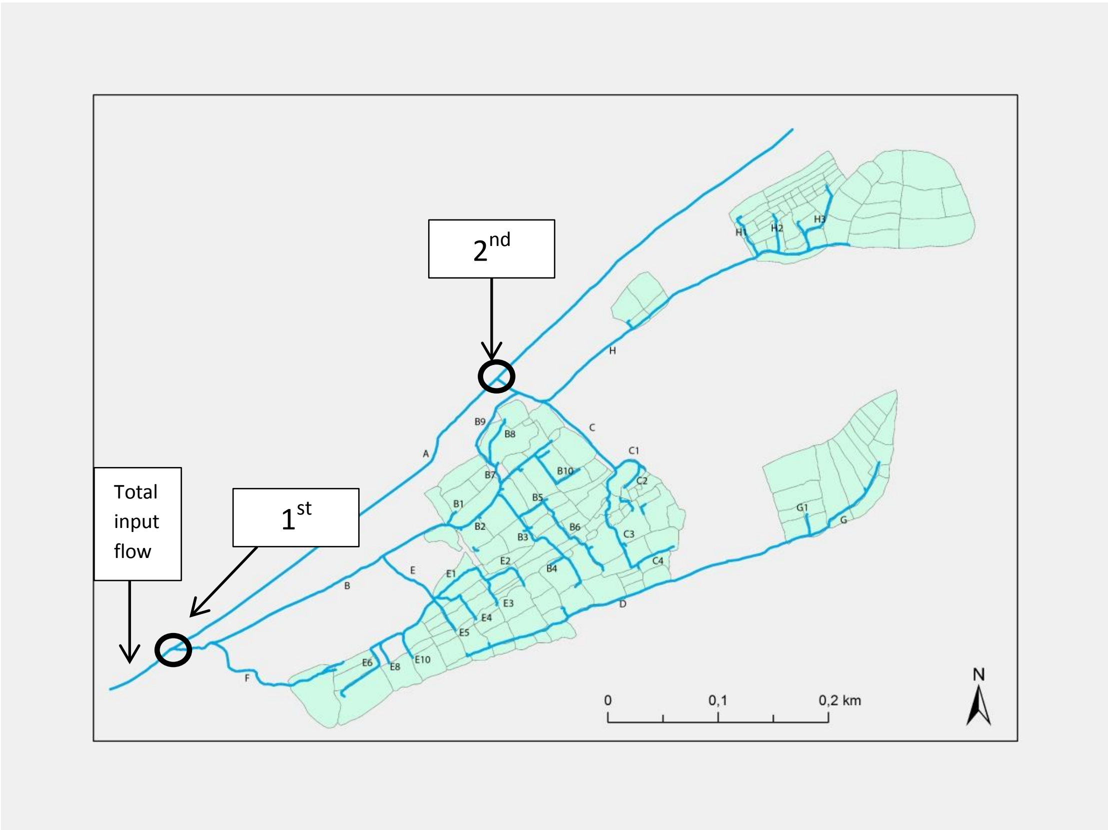

Figure 27. Location of the two inputs in the system.

6.2 Canal system H

System H is really unique for the general irrigation system because it has small canal dimensions in comparison to the other canal systems, especially given the fact that it irrigates 26% of the total irrigation area. This is the second largest area to be irrigated by a canal system (after canal system B which irrigates 28% of the total area). Simulations were performed in order to understand how realistic some stone settings are in regard to the dimensions of canal system C. Stones were put in different places in the system.

Remarks from results: If water is diverted from system C, for the high flow scenario, the water level in canal system H exceeds the maximum by 100%. If not, the water level is in a permitted height. In the low flow scenario, for any stone setting, water level in system H is realistic.

6.3 Canal system C and H

In order to understand the hydraulic reasons for the relatively small canal dimensions in system H and the role of system C, simulations were performed. In one set of experiments elevation data were changed so that the average slope in the two systems is the same. The second set of experiments focused on the width of the canal systems.

Remarks from results: In the present situation of slopes and canal dimensions, canal systems C and H get almost the same amount of water (in the high flow scenario). The slope in canal system C is relatively flat but this is reimbursed by its large width. If canal systems had the same slope and the present widths, then the largest portion of water goes to system C. If the systems had the same width with the present canal dimensions then canal system H gets more water. The set shows that canal system C is constructed in a way to get equal portion of water with H even though it irrigates a smaller area.

6.4 Experimenting with Management styles

The scenarios that were entered in the simulation were strategically chosen. The purpose was to gain insights about the system with the least possible simulations. The simulations focused on three systems; system C, system B and system H. Systems C and H are irrigated from the same input source and they share water if there is no diversion of water. They can show the result of different management types in dependent systems. Also, canal system B was chosen as a third representative because it irrigates the largest area from the first input. Concerning the flows, two scenarios were used about the total discharge in the system; in the first one the total input discharge is 80% of the maximum that fits the canal of the main water system and the second is 20% of the maximum. Although the flows are unknown, assuming that the system at some point could have functioned with the maximum input discharge these scenarios serve analogically as a high and low discharge scenario. The above scenarios were further specified with three different irrigation types. The first one is irrigation with no stones in the canal systems. In this case, simulation shows what happens to the fields without any human actions. Secondly, one where there is a maximum of one stone in each field. And finally, one where stones are also put in main canals to prevent water from running away from a specific cluster of systems at a time.

Time step of the simulation is 1 min and the simulated period is 2 days. The scenarios along with the steps taken in each one are:

Steps for the type A scenarios:

- Simulate with Sobek 1D after removing all stones.
- Observe the flow in each field.

Scenarios:

A.1. No stones-80% of maximum input discharge.

A.2. No stones-20% of maximum input discharge.

Observation:

Some fields in canal system H and G do not get water at all, while others have really high water levels.

Remarks:

It is clear that in order to irrigate all the fields effectively, human actions are needed.

Steps for the type B scenarios:

- Simulate with Sobek 1D after putting stones in canal systems if prescribed.
- Extract reach flows Q_{in} and Q_{out} for the most upstream field in the system (Figure 29). If the field belongs to a sequence of fields with dependency, then Q_{out} is the flow in the first reach of the next system. If not then Q_{out} is considered to be zero because no flow is considered to leave the system from the fields. This is an expression of the borders in the fields.

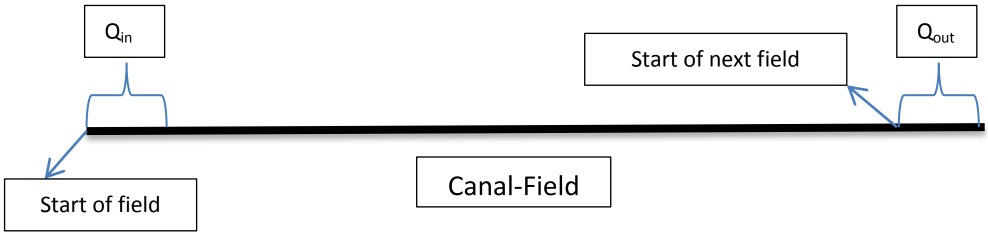

Figure 28. Location of Qin and Qout.

- Calculate the water balance and mark the time in which the duration of irrigation is completed.
- If Q_{out} is zero then we put a stone in the start of the system from the time of irrigation completion until the end of the simulation period. If not, the water balance for the next fields of the set is calculated. The minimum amount of stones is placed in the entrances of the fields in order for sufficient irrigation to be achieved in all the fields.
- Simulate again in order to find the flows after the stone settings.
- Extract reach flows Q_{in} and Q_{out} for the next most upstream field in the system. An example in shown in Figure 30.

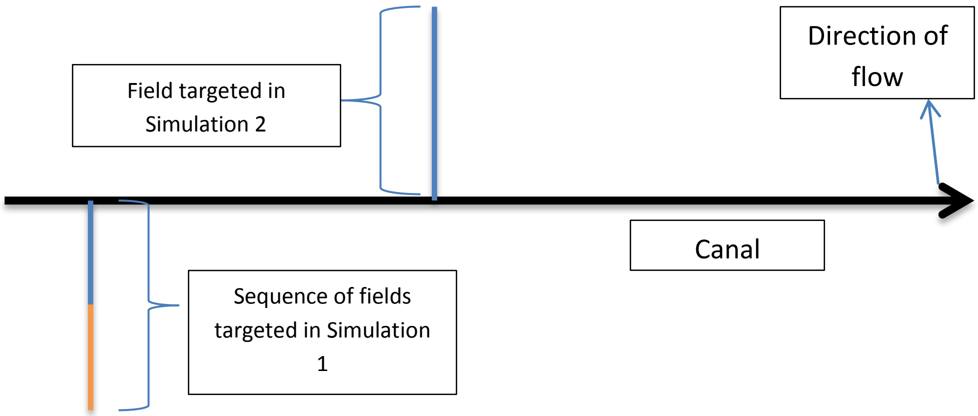

Figure 29. Relation of fields in two consecutive simulations.

B.1. Stones in fields after completion of irrigation-80% of maximum input discharge-no stones in main canal systems. Goal: to understand the distribution, dependencies, priorities in the fields and volumes of flows in the high flow scenario.

Results:

- It takes at least 112 min to irrigate under these conditions the area that correspond to canal system C. In this time, 19 stones are put in the system.
- It takes at least 372 min to irrigate under these conditions the area that correspond to canal system H. In this time, 33 stones are put in the system.
- Some fields (Figure 31) that are irrigated from canal system H do not get water before the placement of stones in main parts of the canal system H.

Figure 30. Fields with no flow of water without stones in the main canal system.

- When there is a sequence of fields and the most downstream field is relatively large, the last field needs more time to be irrigated than the first one. This means that the first field in the row gets surplus of water in the attempt to irrigate all the fields because water has to pass from this field with this modeling scheme.

Remarks: In this set-up it is not possible to irrigate first the downstream fields and then the upstream. This is because the downstream ones may not get water at all before the stones are placed in the system. In the case of a sequence of fields on the other hand, in order to ensure sufficient irrigation stones are put only after the last field is irrigated.

B.2. Stones in fields after completion of irrigation-80% of maximum input discharge- stone in canal system H (Figure 32). Goal: to track differences in flows and irrigation time for system C when system H is closed and to find the irrigation time for system B.

Figure 31. Location of stone in Scenario B.2.

Results

- It takes at least 48 min to irrigate under these conditions the area that corresponds to canal system C. In this time, 16 stones are put in the system.
- It takes at least 97 min to irrigate under these conditions the area that corresponds to canal system B. In this time, 33 stones are put in the system.

B.3. Stones in fields after completion of irrigation-80% of maximum input discharge- stone in canal system H + input 1 (Figure 33). Goal: to track differences in flows and irrigation time for system C when more canal systems are closed.

Figure 32. Location of stones in Scenario B.3.

Results:

- It takes at least 36 min to irrigate under these conditions the area that corresponds to canal system C. In this time, 17 stones are put in the system.

B.4. Stones in fields after completion of irrigation-80% of maximum input discharge- stone in canal system H + input 1 (Figure 34) to prevent flow in the system. Goal: to track differences in flows and irrigation time for system C gets the maximum amount of water.

Figure 33. Location of stones in Scenario B.4

- It takes at least 22 min to irrigate under these conditions the area that corresponds to canal system C. In this time, 16 stones are put in the system.

Remarks:

It is almost impossible for one person to move all 16 stones in 22 minutes.

B.5. Stones in fields after completion of irrigation-20% of maximum input discharge- stones as in scenario B.3 (Figure 33). Goal: to have insights about irrigation in lower flows and in lower discharge in canal system C.

Results:

- It takes at least 112 min to irrigate under these conditions the area that corresponds to canal system C. In this time, 17 stones are put in the system.

B.6. Stones in fields after completion of irrigation-20% of maximum input discharge- stones are put in canal system F and E (Figure 35) because these affect only flows in B. Goal: to have insights about irrigation in lower flows and irrigation time in system B.

Figure 34. Location of stones in Scenario B.4

Results:

- It takes at least 396 min to irrigate under these conditions the area that corresponds to canal system B. In this time, 31 stones are put in the system.

B.7. Stones in fields after completion of irrigation-20% of maximum input discharge- stones are put in canal system C and input 1 (Figure 36). Goal: to have insights about irrigation in lower flows and irrigation time in system H.

Figure 35. Location of stones in Scenario B.7

Results:

- It takes at least 560 min to irrigate under these conditions the area which corresponds to canal system C. In this time, 33 stones are put in the system.
- Some fields, as in the higher flow scenario, which are irrigated from canal system H do not get water before putting stones in main parts of the canal system H.

C. Stones in fields after completion of irrigation and stones in downstream part of clusters of systems-20% of maximum input discharge- stones are put as in scenario B.6. Goal: to compare irrigation duration with two different irrigation practices.

Steps for scenario C:

- Divide area in clusters of fields (Figure 37).

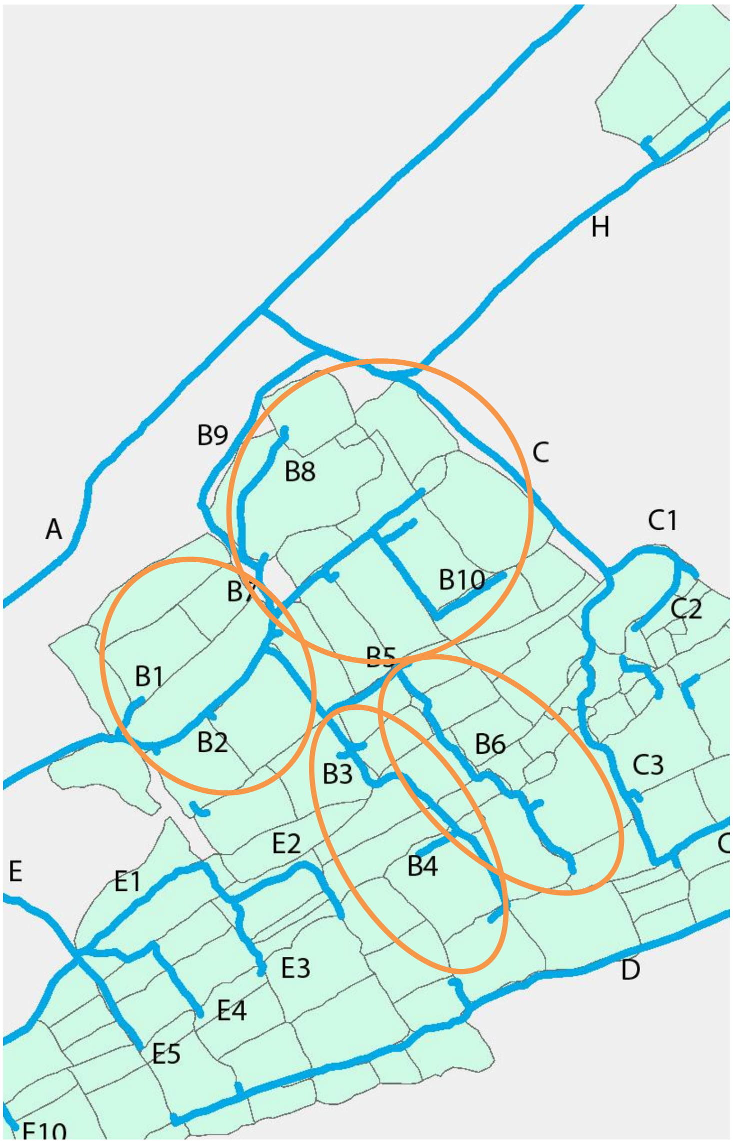

Figure 36. Cluster of fields in system B.

- Place a stone in the end of the first cluster of fields (Figure 38).

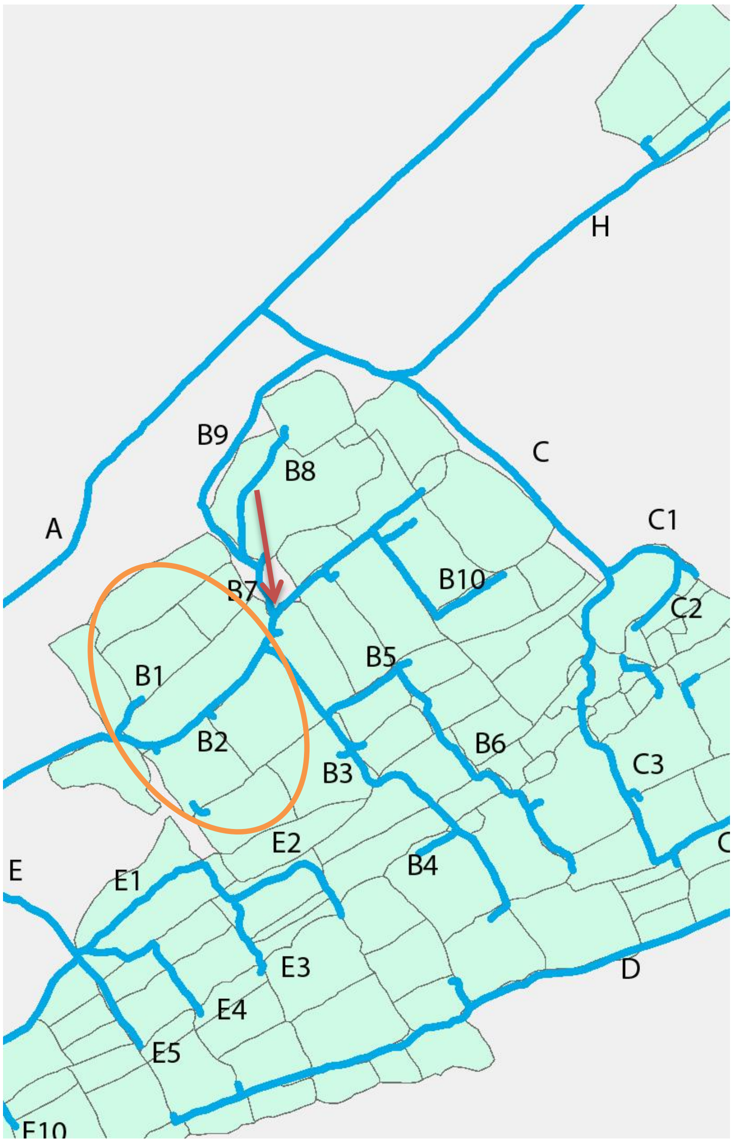

Figure 37. Location of stone for cluster system 1.

- Simulate with Sobek 1D.

- Follow the procedure as in scenario B with the difference that when the last field in the cluster is irrigated the stone is put at the end of the next cluster keeping the non-irrigated clusters without flows (Figure 39).

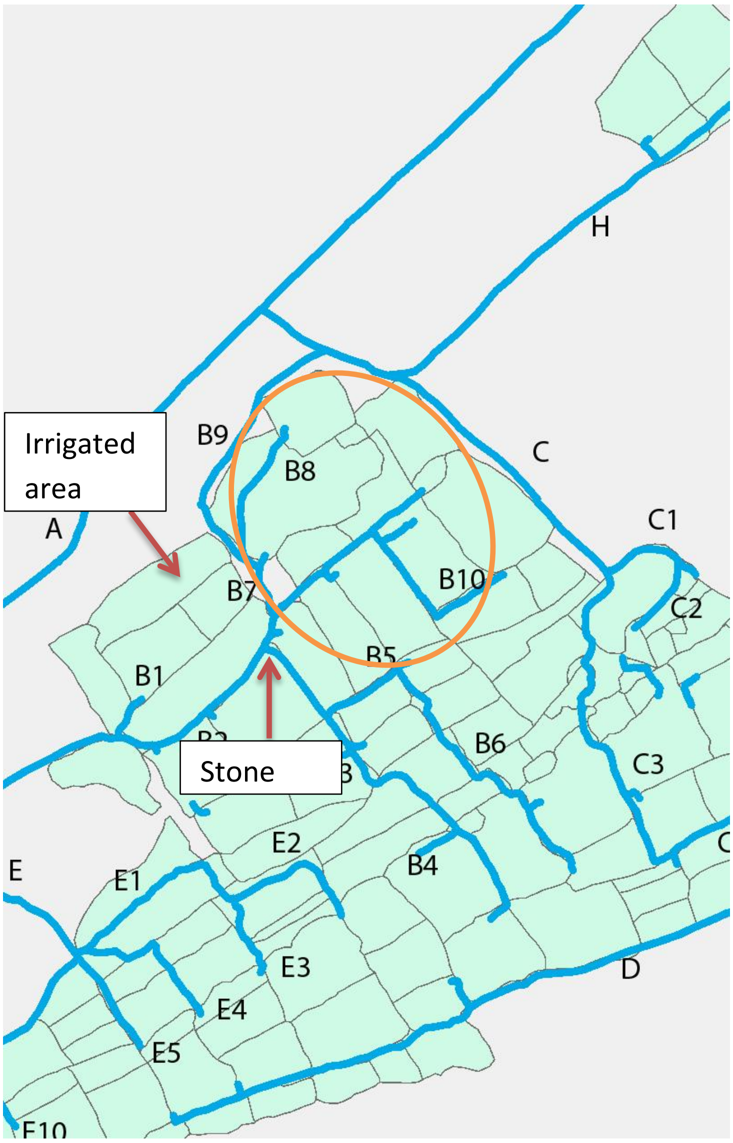

Figure 38. Stone location in the second cluster of fields.

Results:

- It takes at least 580 min to irrigate under these conditions the area that corresponds to canal system B. In this time, 31 stones are put in the system.

Remarks from results:

It takes more time to irrigate one cluster of fields at a time.

6.4.1 Synopsis of results

Table 10. Synopsis of results from experimentation with management styles.

Scenario	Irrigation tecnhique	Input discharge	System	Duration of irrigation in system	Number of stones
All open	Parallel irrigation	80% of max	All	28 fields with no water	none
All open	Parallel irrigation	80% of max	All	130 fields with no water	none
All open	From upstream to downstream	80% of max	C	112 min	19
All open	From upstream to downstream	80% of max	H	372min	33
All open except for H	From upstream to downstream	80% of max	C	48min	16
All open except for H	From upstream to downstream	80% of max	B	97min	31
1st itake closed +H closed	From upstream to downstream	80% of max	C	36min	17
Everything except from C closed	From upstream to downstream	80% of max	C	22min	16
1st itake closed+ H closed	From upstream to downstream	20% of max	C	113min	17
1st itake closed+ C closed	From upstream to downstream	20% of max	H	560min	33
Open only B in 1st input	From upstream to downstream	20% of max	B	396min	31
Open only B in 1st input	Clustered fields	20% of max	B	580min	31

6.5 Flows and irrigation time

In the end all the different scenarios of the same management type can be translated into different flows in each canal system. Scenarios B1-5 provide information about how different flows change irrigation time for system C under the same management practices. In order to quantify the results, an indicator, IrrEf, is calculated:

$$IrrEf(i) = \frac{Irrigation\ duration(i)}{[Area(i) * \left(\frac{Input\ discharge(i)}{60}\right)]}$$

Where <Irrigation duration(i)> refers to the scenario i where C gets <Input discharge(i)> in m_3/s. The area is the same in the case of system C. The units of IrrEf are min^2/m^5. The purpose of this indicator is to serve as a converter of input flow into irrigation duration given a certain area (Table 11).

Table 11. IrrEf for different scenarios refering to C system.

Scenario	IrrEf	Input discharge in C (m^3/s)	Irrigation duration (min)	Area (m^2)
B4	0,0002	0,3053	22	5275
B3	0,0008	0,1489	36	
B1	0,0163	0,0216	112	
B2	0,0031	0,0496	48	
B5	0,0233	0,0153	113	

From Figure 40 we can conclude that the results follow a curve:

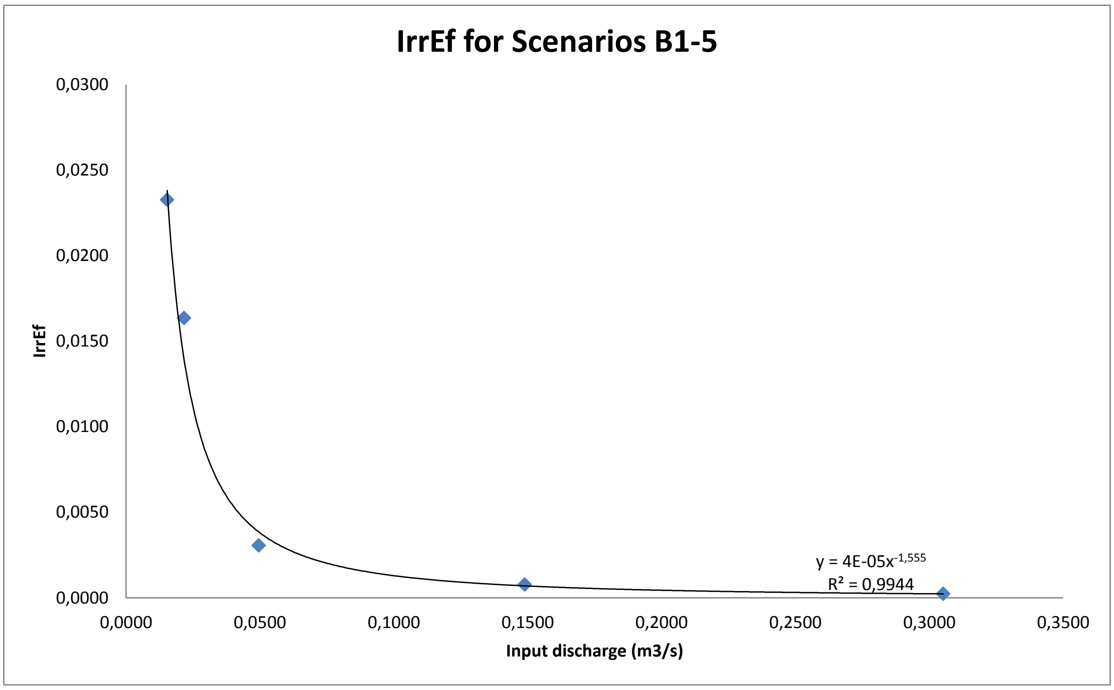

Figure 39. Chart of IrrEf for Scenarios B1-5.

If we add the results from the other B scenarios we can see (Figure 41) that the curve remains more or less the same. This means that the curve can be used for all the canal systems. More specifically, if we have a canal system that receives a specific input discharge we can find from this curve the IrrEf. With the IrrEf, the area of the region and the specific input discharge we calculate the irrigation duration. It is important to note that this duration corresponds to the management practice in which the system is irrigated from upstream to downstream and to the stones are put after the irrigation completion.

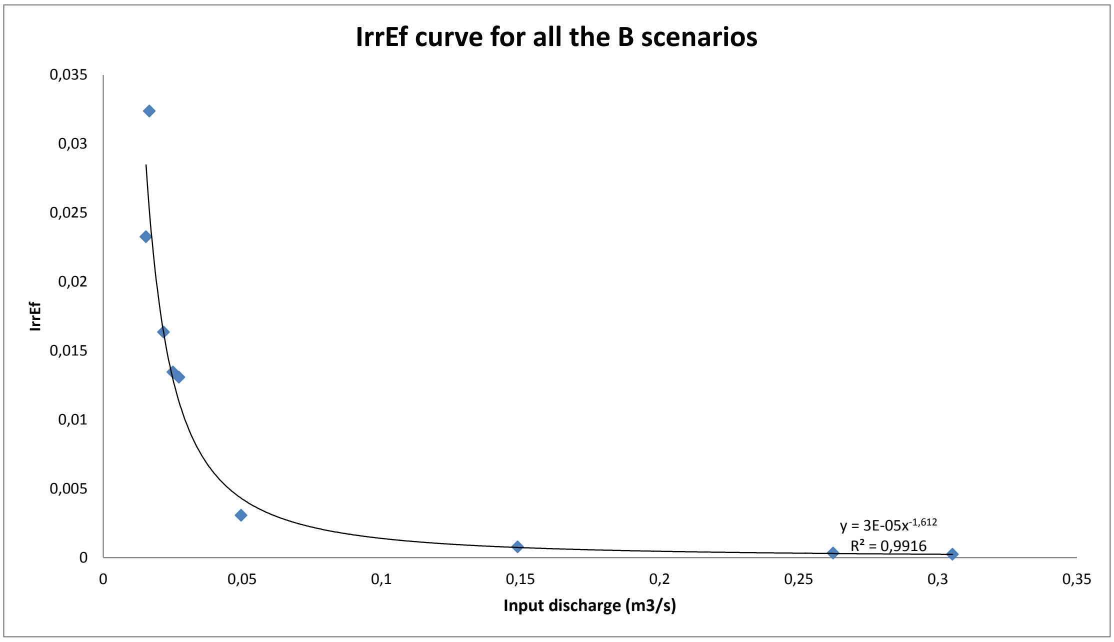

Figure 40. Chart of IrrEf for all B Scenarios.

The practical meaning of the curve is that if we lower the total discharge in the subsystems the duration of irrigation increases in a non-linear way.

6.6 Irrigation duration of the system

We can use the IrrEf to estimate the irrigation duration in any system without the time consuming steps described in type B Scenarios. Two scenarios of management (Simultaneous irrigation and Irrigation for one system at a time) and two scenarios of total discharge (20% of total discharge and 80% of total discharge) were implemented.

6.6.1 Simultaneous irrigation from upstream to downstream

The steps for the scenarios of simultaneous irrigation are:

- Simulate with Sobek 1D.
- Convert each system's input discharge to irrigation duration. In order to do that we find the IrrEf from the curve for the observed input discharge. Then we multiply the converter with the area and the input discharge. This is how we find the irrigation duration.
- Close with a stone the first system to be irrigated.
- Calculate the areas which were irrigated in the rest of the system.
- Simulate again to find the new flows in the canal systems.
- Convert the input discharge to irrigation duration for the remaining areas of each system.
- Close the first system to irrigate all of its remaining area.
- Simulate again and follow the same procedure.

Table 12. Example of calculation step of the procedure.

	System C	System B	System H	System F	System E	System D+G
Discharge (m^3/s)	0,031	0,144	0,040	Already irrigated	0,114	0,024
Area (m2)	5275,000	18177,497	16810,581		9029,113	11241,913
Time/(area*input)	0,008	0,001	0,005		0,001	0,012
Estimated duration in min	79,456	106,984	217,426		61,229	199,266
Area irrigated (m^2)	4064,953	10403,395	4734,013		9029,113	3454,334
Area to be irr (m2)	1210,047	7774,102	12076,568		0,000	7787,579

Results:

- With 80% of the maximum total input discharge in the system, total time of irrigation is 2hours and 40 minutes. In this time approximately 125 stones will be put in the fields. This corresponds to 1 stone every 1min and 16s.
- With 20% of the maximum total input discharge in the system, total time of irrigation is 8hours and 45 minutes (125 stones). This correspond to 1 stone every 4min approximately.

The following figures show the change of input flow with time during irrigation. Each line represents a different canal system. When the irrigation is completed and a stone is put on a canal system, there is sudden drop in its line. On the other hand, when there is a sudden rise in a line, it means that flow has suddenly become available due to irrigation completion in other canal systems. We can conclude that in high flows the canal systems (B,E,D,G,F) that connect with input one have priority in flows in general (Figure 42), whereas system C has high flow in regard to the area it irrigates (Figure 43). In lower flows, on the other hand, systems H and E seem to be in priority (Figures 44 and 45). The canal systems that keep their priority in both flow scenarios are E and F.

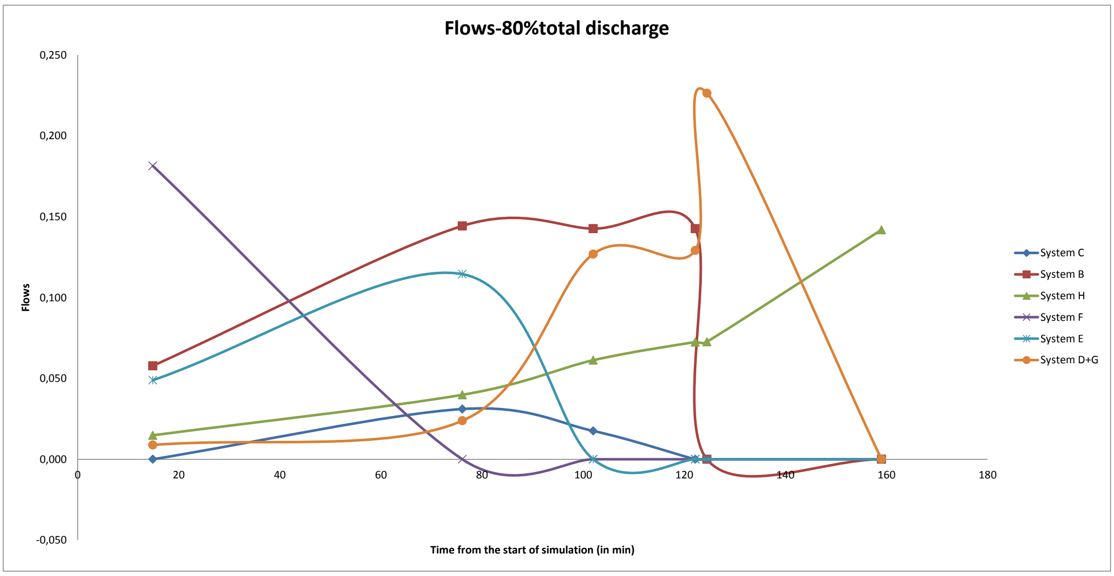

Figure 41. Evolution of discharge in each system with the progression of time and the placement of stones (80% of total discharge scenario).

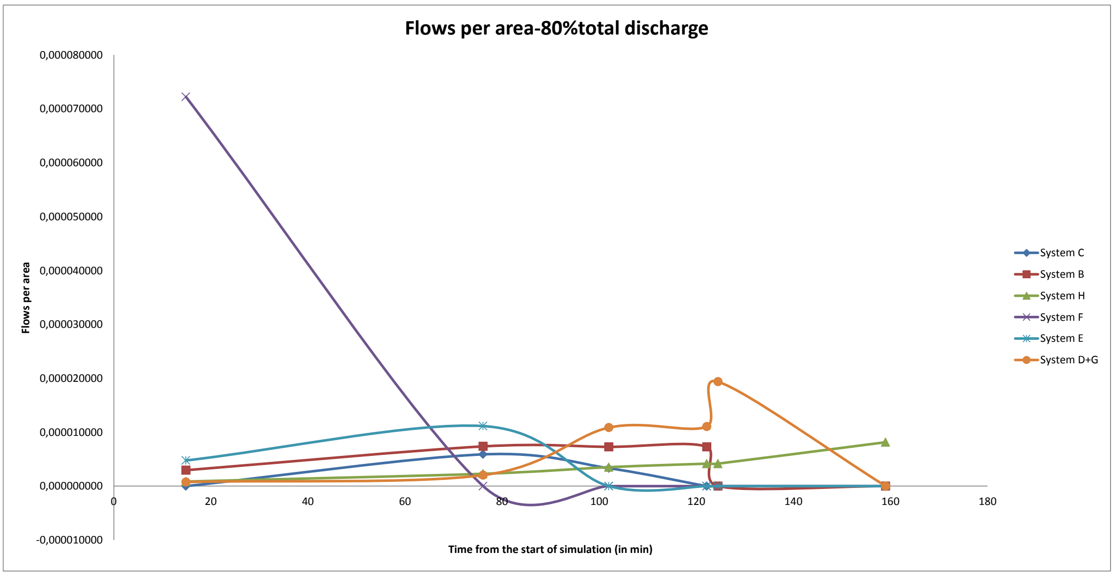

Figure 42. Evolution of discharge per area in each system with the progression of time and the placement of stones (80% of total discharge scenario).

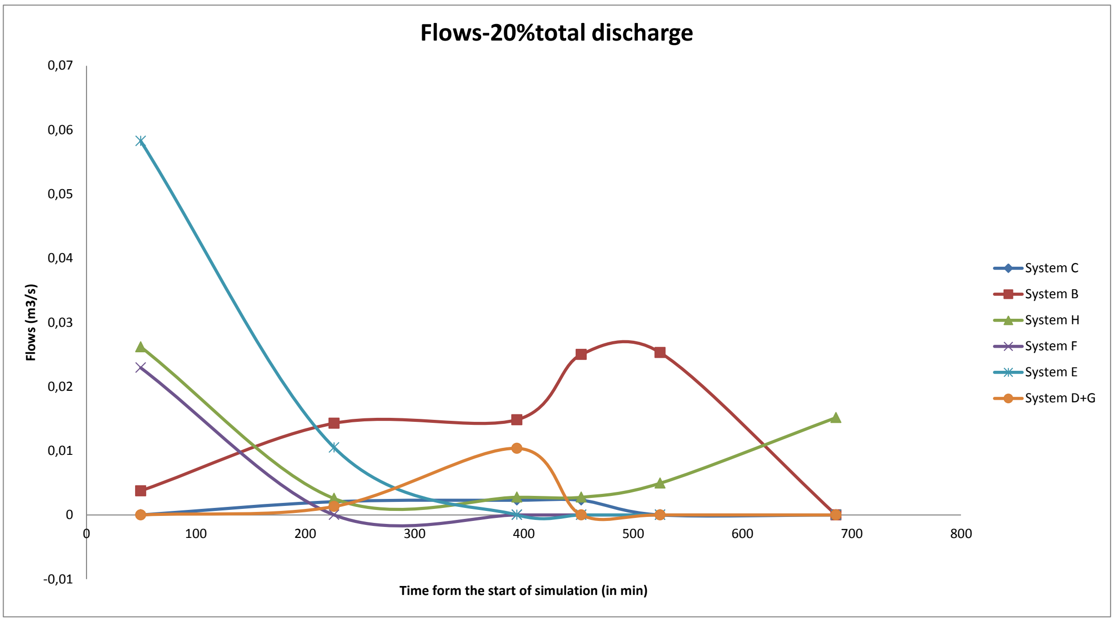

Figure 43. Evolution of discharge in each system with the progression of time and the placement of stones (20% of total discharge scenario).

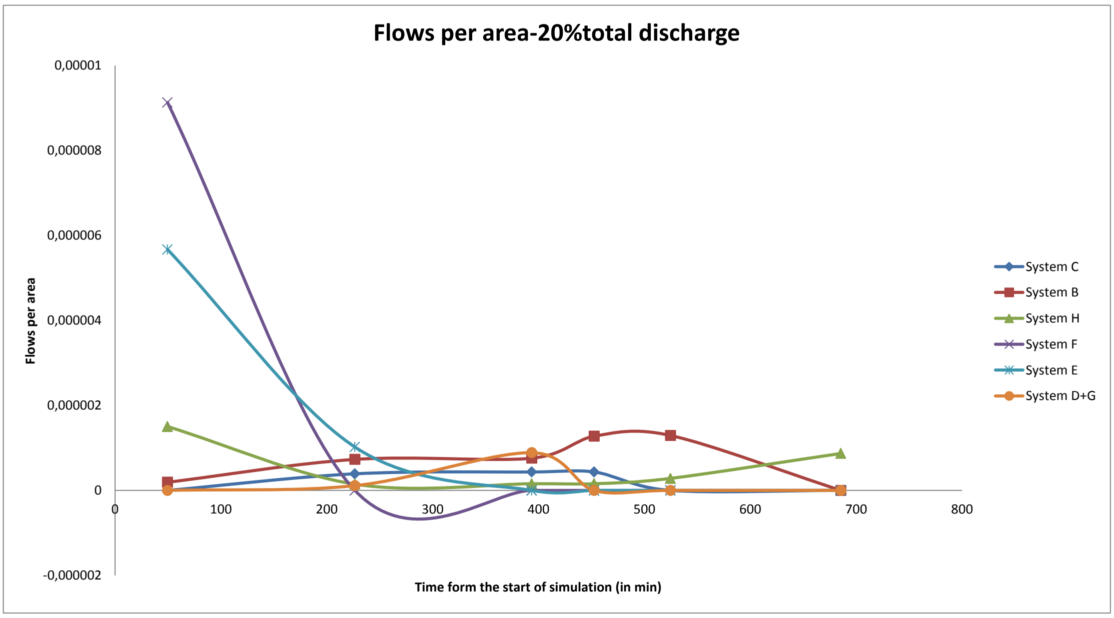

Figure 44. Evolution of discharge per area in each system with the progression of time and the placement of stones (20% of total discharge scenario).

6.6.2 Irrigation of one system at a time from upstream to downstream

The steps to calculate the irrigation duration of one system at a time are:

- Place stones so that only one system gets water at a time.
- Simulate with Sobek1D to find the input flow in the system.
- Calculate with the converter the irrigation duration.
- Repeat for every system.
- Add the irrigation duration of each canal system.

Results:

- With 80% of the maximum total input discharge in the system, total time of irrigation is 5 hours and 3 minutes. In this time, approximately 125 gates are put in the fields. This corresponds to 1 gate every 2min and 25s.
- With 20% of the maximum total input discharge in the system, total time of irrigation is 21hours and 49 minutes (125 gates). This correspond to 1 gate every 10min and 30s.

General remarks:

It takes longer (almost 4 times longer) to irrigate when the irrigation is done separately.

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7. Analyzing the results

7.1 Falaj system

The fact that the main water system seems to derive from the mountains, combined with its massive length, link to a spring or groundwater type source. Also, the water system is located in higher elevation than the wadi and although the two are at some places close the one to the other, a diversion canal was not found. In conclusion, most probably the flow in the system was rather stable.

7.2 Stone stories

For each management practice simulated, a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis is performed. The S and W are based on the results of the simulations. In the end, each practice is evaluated in order to understand how plausible its implementation was in this system.

7.2.1 Simultaneous irrigation of all fields-No intervention

Description: The system consists only of the canals, the borders and the walls.

S: No effort from the farmers is put in the system except for canal maintenance.

W: Irrigation in some parts is not possible (in the low flow scenario 130 of the 180 fields), some fields get more water than the amount needed and there is no water allocation.

O: In fields with surplus of water, perennial crops could be cultivated. Inhabitants in the settlement can take on other duties and have more overall production of goods.

T: We expect water clogging in case of high flows in the fields with priority and damage in crops in fields with low priority.

Evaluation: The technique could be implemented if the inhabitants could be employed in a more productive occupation and the agriculture could bring more benefits. Because the flows are different between the fields, if farmers owned the fields, power relations and conflicts between the farmers would occur. If the community owned the fields, differences in flows would not cause any problem.

7.2.2 Parallel irrigation from upstream to downstream

Description: When the water demand has been satisfied in a field, stones are used to prevent additional flow. When all the fields that correspond to a canal system have been irrigated then a stone is put in the canal system.

S: Irrigation time is the minimum among the examined management styles.

W: The amount of labor needed for the system to function is the maximum among the different techniques. This is reflected by the amount of stones that need to be relocated in the system. From 1 stone every 2 minutes to 1 stone every 10 minutes for several hours of work, this practice needs a lot of co-ordination especially if we take into account that two consecutive stone placements may be located far one from the other. Another weakness is the fluctuation of flows in each field due to the constant opening and closing of gates. This makes water rights complicated.

O: Fluctuations in flow do not have a considerable impact in irrigation duration.

T: Farmers must be in good terms and co-operate with each other.

Evaluation: This practice is beneficial if there is a time limit for using the main water system, otherwise it is very complex, requires a lot of labor force in a small period and it can easily provoke conflict.

7.2.3 Irrigation in clusters of fields from upstream to downstream

Description: Water is diverted with stones so that only a number of fields are irrigated at a time.

S: The irrigation scheme is less complex, irrigation duration is at a plausible level and water is more easily allocated.

W:-

O: Clusters can be given more easily priority so that the crops are protected and irrigated more often. In these clusters it would be easier to grow trees.

T: In case of dry spells, time can begin to stress the system.

Evaluation: Given that the duration of irrigation does not exceed a time limit set for the irrigation system, this choice seems really efficient in terms of labor needs. We could argue that the entire system could rely on one team of farmers that irrigates one cluster at a time.

7.2.4 One field at time irrigation

Description: Flow is allowed in one field or sequence of fields at a time. This was not modeled but we can make assumptions about the results.

S: Irrigation scheduling is simple, co-ordination is simpler and water shares are more just and can be allocated per field.

W: Irrigating in clusters of subsystems takes four times more than irrigating in parallel all the fields. When the modeling changed from clustering on canal systems to clustering on a group of fields, irrigation duration increased by 47%. Therefore, if we implement the extreme case of clustering, which is irrigating a field at a time, we expect the irrigation duration to increase in an unsustainable level. Also, high flows in the canal systems may prove difficult to control.

O: In the event of a conflict between users of the system this practice provides the most equal flows.

T: In the event of high flows, in canal system H water exceeds maximum water level with this practice.

Evaluation: The high duration of irrigation makes the practice problematic. In the event of high flows, the duration decreases and the practice can be implemented. While implementing this method, it is possible to irrigate two fields in completely different locations with the proper synchronization. The labor density is low and, as in the previous case, the system could function with few farmers at a period.

7.3 Ownership

In a sequence of fields, the upstream field needs to be opened for irrigation to be successful especially when one of the downstream fields is larger in size. If the fields are owned by different farmers, the owner of the upstream field has power over the owner of the downstream one. Earthen canals that have been dug in the fields do not enhance the power relation because they can be easily altered.

Another aspect of ownership is the distance between the owned fields. Due to the fact that high flows are dispersed, farmers can have benefits by owning fields in different parts of the system. On the other hand, if a farmer has to irrigate the fields in a specific hour of the day, it is difficult to ensure sufficient irrigation in two distant fields.

7.4 Downstream field systems

For the simulated flows, for the specific demand and for the simulated management types, the duration of the irrigation of the system is less than 35% of the total available time, and as a result the downstream water systems have their own share of water for irrigation. Due to the fact that water is shared in all systems, it is logical to assume that a local committee must have been present to promote co-operation of the systems. Otherwise the upstream irrigation system could have exploited its power position and could have reduced the capability of irrigation in the downstream systems. Another reason why local co-operation would be beneficial is for setting the irrigation time frames of each system. When the system draws water from the main water system, the flow in the latter is reduced by 90%. Without a specified time frame, irrigation in the downstream field system cannot be scheduled. If irrigation is not scheduled, it becomes difficult to collect the number of farmers required to work in the fields. Even if there is time for irrigation, without the proper labor force irrigation cannot be achieved. This can result in frustration and conflicts between the users of the downstream water systems and the users of the upstream ones.

7.5 Remarks

The previous analysis was done for a specific irrigation interval of specific water needs. By increasing the frequency of irrigation in a period of time the water needs per irrigation decrease and by decreasing the frequency the water needs increase. As for the total water needs it is safe to say that most seasonal crops had less water needs. The existence of date palms makes up for the extra (estimated) water and only if date palms were cultivated in a high percentage of the total area the total water needs would have been higher than those in the calculations. Overall, errors occurring from using wrong water demand lead to over or under estimation of irrigation duration. All the other results are valid.

7.6 Conclusions

In this system, the results suggest that the choice of the irrigation technique seems to be restricted by the available time and the available labor force. Although the general patterns are valid one would wonder if the input flow scenarios were optimistic. If this is the case then a combination of parallel irrigation with cluster irrigation has a better chance to have occurred. Otherwise, in order to avoid conflicts a simpler choice would be to irrigate in clusters. In any case, when dry periods occur, farmers need to co-operate more in order to achieve the right results. Co-ordination on the other hand, has more to do with the ownership of the fields and the choice of what fields to irrigate in parallel.

7.7 Results and traditional agriculture

Traditional agriculture proposes:

- Priority to domestic use. The main settlement is located near the second intake. If we consider the priority described in traditional agriculture, then water must be drawn from a point that always has water and is located before agricultural use. This limits the parts where water can be drawn for domestic use in the points shown in the map of Figure 1. The first point is in the main channel. One of the buildings could serve as a mosque. The main channel is the only point where water passes through even when there is no irrigation. Intake 1 is hydraulically connected to the potential locations of domestic use. This is why it needs to be controlled so that domestic needs are satisfied uneventfully.

Figure 45. Potential location of intake for domestic use.

- Priority to perennial crops. According to the figures inherent priority is given to canal systems F,E,B in the 80% of max discharge scenario and to canal systems F,E,H in the 20% of max discharge scenario. Also the upstream fields get water first. Potential locations of perennial crops are the upstream fields of the systems with consistent priority F and E (Figure 2).

Figure 46. Potential location of fields with perennial crops.

- Water shares based on time. Parallel irrigation, as described previously, creates uneven flows throughout the system, making water rights based on time also uneven. It seems that this practice would possibly raise conflict between the farmers.

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8. Results from the Simulation process

8.1 About the control mechanisms

Observation 1: The simulation of the flows for both input scenarios (20% and 80% of maximum flow) with no stones (Irrigation scenario: Everything open) showed that some fields do not get water while other flood.

Conclusion: Assuming that all the fields were simultaneously in use, the lack of flow in several fields indicates that the system requires a control mechanism to function.

Observation 2: Irrigation duration increases when it is done for one cluster of fields each time.

Conclusion: Large number of control mechanisms does not yield more efficient irrigation in terms of time.

Observation 3: Stones in main canal systems that divert water away from fields that have already been irrigated with sufficient amounts of water, lower the total irrigation time.

Conclusion: The importance of control structures is highlighted again in order to have more efficient irrigation in terms of time.

8.2 About the irrigation management

Observation 4: When linked together, the upstream fields get more water than needed to achieve sufficient amount of irrigation in the downstream fields.

Conclusion: The way the system was modeled (one opening from field to field) supports the downstream to upstream irrigation method. This means that in order to have irrigation from upstream to downstream other means of connections between consequent fields must be used. The earthen canals and multiple openings in each field are examples of such connections.

Observation 5: The irrigation practice which yielded the minimum irrigation duration needed the most labor force and co-ordination.

Conclusion: Users of the system had to choose between time and energy spent on the system. Also, if the users did not co-operate well they may had to spend more time to achieve successful irrigation of the system.

8.3 About conflict and co-operation

Observation 5: Inherent power relations concerning water exist between consecutive fields, the two intakes of the system, the irrigation system and the downstream systems and finally between field systems.

Conclusion: Power relations means that there is a predisposition for conflict. In order for all the inhabitants to get their share of water in order to survive there must have been agreements between the users. This can be linked to a local authority.

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