NATIONAL TECHNICAL UNIVERSITY OF ATHENS

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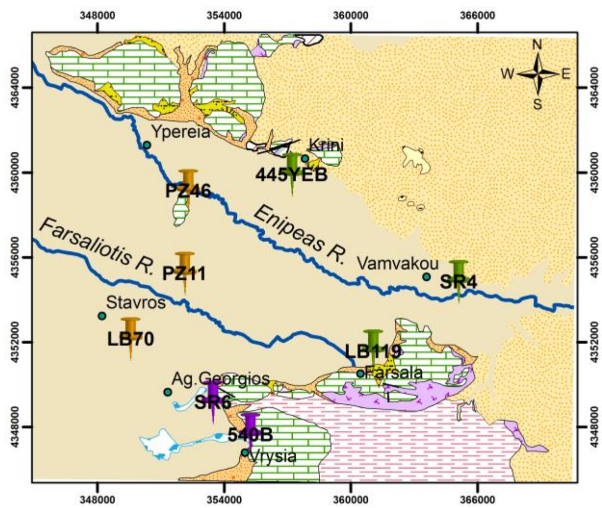
«GEOINFORMATICS»

INTERPRETATION OF GROUNDWATER HYDROGRAPHS IN THE WEST THESSALY BASIN, GREECE, USING PRINCIPAL COMPONENT ANALYSIS



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Athens, June 2016

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Stamatina Seferli

Academic Supervisor: K. Modis, Associate Professor NTUA

Has been accepted by the tripartite committee at 30th June 2016

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ABSTRACT

The scope of this work is to elucidate the use of Principal Components Analysis (PCA), a multivariate statistical procedure, as a tool to interpret the areal distribution of various types of water level fluctuation patterns within the watershed of Western Thessaly in Greece. In this area, intense ground water abstraction takes place during the last decades to cover the needs of agricultural activities, and is reported to have impacted significantly the ground water regime.

For convenience, the study area was divided into three subareas, namely Farsala, Karditsa and Trikala, each of them containing a series of monitoring wells. In each of these areas, the water level variations for the past 40 years where examined thoroughly through plotted hydrographs. Then, PCA was applied in order to define a few uncorrelated linear combinations of the original hydrographs, which summarize the data set without losing much information. PCA revealed the existence of distinct temporal patterns in the available water level data, allowing the classification of wells into groups of similar behavior.

The interpretation of the ground water level measurements with PCA can be used by the stake holders involved in ground water management (farmers, public authorities, general public, ecologists, etc.) to closely monitor the aquifers piezometry, through the identification of certain target wells from larger well groups. These target wells can be selectively measured in the long - term, allowing the sustainable monitoring and the collection of reliable ground level data.

ΠΕΡΙΛΗΨΗ

Η διαχείριση του νερού λόγω υψηλών αρδευτικών αναγκών είναι ένα μείζον θέμα που παρατηρείται τα τελευταία χρόνια σε πολλές περιοχές της χώρας μας και έχει απασχολήσει κατά καιρούς δεκάδες φορείς που προσπαθούν να διαχειριστούν το θέμα με τον καλύτερο δυνατό τρόπο.

Η Θεσσαλική πεδιάδα είναι μια από αυτές τις περιοχές, καθώς η άρδευσή της πραγματοποιείται αφενός μεν με γεωτρήσεις άντλησης υπογείων νερών και με διοχέτευση επιφανειακών νερών από τον Πηνειό ποταμό μέσω πολλαπλής χρήσης στραγγιστικού-αρδευτικού δικτύου, αφετέρου δε με χρήση νερού από μικρούς ταμιευτήρες, όπου αποθηκεύεται το πλεονάζον νερό που κινείται μέσα στο δίκτυο μέχρι την έναρξη των αρδεύσεων. Αναφορικά με τα υπόγεια νερά, αυτά εκμεταλλεύονται μέσω ενός πλήθους κρατικών και ιδιωτικών γεωτρήσεων οι οποίες έχουν ξεκινήσει από τη δεκαετία του 1970. Σημειώνεται μάλιστα ότι αποτελεί ένα από τα πιο ελλειμματικά διαμερίσματα της ηπειρωτικής χώρας σε νερό.

Ειδικότερα, όσον αφορά τη λεκάνη της Δυτικής Θεσσαλίας που αποτελεί και την περιοχή μελέτης, οι τοπικοί υδατικοί πόροι, επιφανειακοί και υπόγειοι, παρά την ενίσχυσή τους από τις εκροές παράπλευρων ταμιευτήρων που έχουν κατασκευαστεί για το λόγο αυτό, δεν επαρκούν για την κάλυψη των απαιτήσεων σε αρδευτικό νερό των υφιστάμενων καλλιεργειών. Η έλλειψη επάρκειας σε έργα ταμίευσης σε συνδυασμό με τον μη ορθολογικό προγραμματισμό των καλλιεργειών, έχει οδηγήσει σε σημαντικό περιορισμό της θερινής ροής των ποταμών και δραματική υποβάθμιση των υδροφορέων, εξαιτίας της εντατικής χρήσης αρδευτικών γεωτρήσεων.

Πιο αναλυτικά, το μεγαλύτερο τμήμα των υδροφόρων οριζόντων της Δυτικής Θεσσαλίας βρίσκεται κάτω από καθεστώς υπεράντλησης, η οποία ορίζεται ως «εντατική απρογραμμάτιστη και μη ελεγχόμενη “εκμετάλλευση” των υπόγειων νερών, συνοδευόμενη από οποιεσδήποτε ανθρώπινες παρεμβάσεις στο υπέδαφος που λειτουργούν αποστραγγιστικά, αφαιρώντας συχνά από τους υδροφορείς ποσότητες νερών μεγαλύτερες των υπερετήσια ανανεώσιμων υπόγειων υδατικών αποθεμάτων» (Κουμαντάκης, 2001). Είναι μια κατάσταση που οδηγεί σε εγκατάσταση καθεστώτος αρνητικού ισοζυγίου των υπογείων νερών.

Με άλλα λόγια, υπάρχει συστηματική ταπείνωση της στάθμης από χρόνο σε χρόνο, ιδιαίτερα κατά το θέρος, όπου το νερό των υδρογεωτρήσεων αντλείται προκειμένου να χρησιμοποιηθεί για τις αρδεύσεις των καλλιεργειών, με συνέπεια τη γενική πτώση της υδροδυναμικής στάθμης. Αυτό που διαφέρει τοπικά είναι η ένταση της υπερεκμετάλλευσης

και ο χρόνος κατά τον οποίο άρχισε η απότομη πτώση της στάθμης των υπογείων υδροφοριών, χωρίς περαιτέρω αναπλήρωση. Από την υπερεκμετάλλευση όμως σε ορισμένες περιοχές απορρέουν κι άλλα προβλήματα που σχετίζονται με την μετακίνηση του εδάφους, καθιζήσεις, κατολισθητικά φαινόμενα και κατά τόπους υφαλμύρινση των υπόγειων υδροφορέων.

Γι' αυτούς τους λόγους κρίνεται απαραίτητη η συστηματική παρακολούθηση της παροχής του Πηνειού και των κύριων παραποτάμων του, καθώς και της στάθμης του υδροφορέα, καθώς θεωρείται αναγκαίο βήμα για την αξιόπιστη εκτίμηση του υδατικού δυναμικού της Δυτικής Θεσσαλίας, επιφανειακού και υπόγειου, και τη λήψη των αναγκαίων διαχειριστικών μέτρων.

Με αφορμή τα προβλήματα που υπάρχουν στη συγκεκριμένη λεκάνη, μελετήθηκε πλήθος γεωτρήσεων σε όλη την έκτασή της, με σκοπό την ερμηνεία υδρογραφημάτων υπόγειου νερού, με τη χρήση Ανάλυσης Κύριων Συνιστωσών (PCA). Οι στόχοι που έπρεπε να επιτευχθούν ήταν η εύρεση ομάδων γεωτρήσεων με ομοειδή χαρακτηριστικά που θα βοηθούσαν στη μείωση των γεωτρήσεων παρακολούθησης, εξασφαλίζοντας έτσι εξοικονόμηση οικονομικών πόρων και ανθρώπινου δυναμικού, καθώς και η ανάδειξη της PCA ως εργαλείου ερμηνείας της χωρικής κατανομής των διαφόρων τύπων διακύμανσης της στάθμης του νερού μέσα στη λεκάνη της Δυτικής Θεσσαλίας.

Πιο συγκεκριμένα και για την καλύτερη διερεύνηση, η περιοχή μελέτης χωρίστηκε σε τρεις υποπεριοχές: τις περιοχές γύρω από τα Φάρσαλα, την Καρδίτσα και τα Τρίκαλα, κάθε μια από τις οποίες περιείχε μια σειρά από γεωτρήσεις παρακολούθησης. Ο διαχωρισμός αυτός βασίστηκε στην προϋπάρχουσα ταξινόμηση (κατά Καλλέργη 1970, Sogreah 1974, Κωνσταντινίδη 1978) βάσει υδρογραφικού δικτύου. Η πρώτη περιοχή περιλαμβάνει τον κώνο του ποταμού Σοφαδίτη, την πεδινή περιοχή γύρω από τα χωριά Αγ. Γεώργιο και Σταυρό καθώς και την πόλη των Φαρσάλων. Η δεύτερη βρίσκεται στο Ν-ΝΔ τμήμα της λεκάνης, συμπεριλαμβανομένης της ευρύτερης περιοχής του νομού Καρδίτσας που περιλαμβάνει πολλές ημιαγροτικές και αστικές περιοχές και χαρακτηρίζεται ως «υπόλοιπο Δυτικής πεδιάδας». Τέλος, η τρίτη περιοχή περιλαμβάνει το μεγαλύτερο μέρος της λεκάνης της Δυτικής Θεσσαλίας που διασχίζεται από τον Πηνειό και τους παραποτάμους του Πάμισο και Πορταϊκό.

Στη συνέχεια, με σκοπό την απεικόνιση και κατανόηση της περιοχής και της σχέσης του υπόγειου νερού με τους σχηματισμούς που απαντώνται αναφορικά με την κίνησή του διαμέσου αυτών, κατασκευάστηκαν επιμέρους χάρτες της κάθε περιοχής, καθώς και συγκεντρωτικός χάρτης της λεκάνης με όλους τους λιθολογικούς σχηματισμούς, τη θέση των γεωτρήσεων και τη σχετική θέση των μεγαλύτερων πόλεων. Για τη δημιουργία των γεωλογικών χαρτών χρησιμοποιήθηκαν γεωλογικοί χάρτες του ΙΓΜΕ. Από τους χάρτες αυτούς προκύπτει ότι οι γεωλογικοί σχηματισμοί, οι οποίοι αποτελούν ρυθμιστικό παράγοντα των υδρολογικών συνθηκών της περιοχής, ανήκουν σε 4 κύριες γεωλογικές ενότητες. Στην μεταμορφωμένη Πελαγονική, που περιλαμβάνει γνεύσιους, κρυσταλλικούς σχίστες, φυλλίτες, κρυσταλλικούς ασβεστόλιθους, μάρμαρα και δολομίτες. Στην Υποπελαγονική που περιλαμβάνει σχίστες, ελαφρώς μεταμορφωμένους σχιστο-γνεύσιους, ιλιόλιθους, πηλίτες, ασβεστόλιθους, δολομίτες, οφιολίθους και φλύσχη. Στην ενότητα του Κόζιακα που περιλαμβάνει ασβεστόλιθους, κροκαλοπαγή, ιλυόλιθους και φλύσχη. Τέλος στην ενότητα της Πίνδου που περιλαμβάνει ασβεστόλιθους, πυριτιόλιθους, την ακολουθία του «πρώτου φλύσχη», μεταβατικά προς φλύσχη ιζήματα, φλύσχη. Εκτός των σχηματισμών των ανωτέρω γεωλογικών ενοτήτων, που έχουν δημιουργηθεί κατά την αλπική ορογένεση, συναντώνται και πλήθος νεογενών αποθέσεων όπως άργιλοι, ιλύες, μάργες, ιλυόλιθοι, κροκαλοπαγή, λατυποπαγή και μαργαϊκοί ασβεστόλιθοι, τεταρτογενείς αποθέσεις όπως αλλουβιακές, ποταμοχειμάρριες αποθέσεις, κορήματα και κώνοι κορημάτων, αλλά και η μόλασσα της Μεσοελληνικής αύλακας.

Η περαιτέρω μελέτη βασίστηκε σε 62 γεωτρήσεις παρακολούθησης κατά τη διάρκεια της χρονικής περιόδου 1974 – 2014. Πιο αναλυτικά, 8 γεωτρήσεις μελετήθηκαν στην περιοχή των Φαρσάλων κατά την περίοδο Απρίλιος 1993 – Αύγουστος 2014, 24 στην περιοχή της Καρδίτσας κατά την περίοδο Ιούλιος 1974 – Νοέμβριος 1993 και 30 στην περιοχή των Τρικάλων κατά την περίοδο Απρίλιος 1983 – Ιούνιος 2005. Με βάση τις υπόγειες στάθμες νερών που ελήφθησαν από γεωτρήσεις των συγκεκριμένων περιοχών, δημιουργήθηκαν υδρογραφήματα, ώστε να φανεί η διακύμανση της στάθμης του νερού κατά τη διάρκεια μιας περιόδου 20 έως 23 ετών για κάθε περιοχή και να διερευνηθεί η πιθανή συσχέτιση γεωτρήσεων μεταξύ τους.

Λόγω όμως της πολυπλοκότητας και του μεγάλου αριθμού των υδρογραφημάτων και κυρίως για την αποφυγή θεμάτων υποκειμενικότητας, η ανάλυση αυτή θα ήταν δυνατή μόνον μέσω της εφαρμογής της μεθόδου PCA. Η μέθοδος αυτή καταφεύγει στη δημιουργία δευτερογενών μεταβλητών - υδρογραφημάτων, οι οποίες είναι γραμμικοί συνδυασμοί των αρχικών, έτσι ώστε να είναι ασυσχέτιστες μεταξύ τους και να περιέχουν όσο το δυνατόν μεγαλύτερο μέρος της μορφολογίας των αρχικών. Προκύπτει δηλαδή ένας σημαντικά μικρότερος αριθμός ανόμοιων μεταξύ τους υδρογραφημάτων που ενυπάρχουν σε αντίστοιχες αναλογίες σε όλα τα αρχικά και μπορούν να τα ερμηνεύσουν με αρκετά μεγάλη ακρίβεια. Τα υδρογραφήματα αυτά ονομάζονται Κύριες Συνιστώσες.

Από την εφαρμογή της PCA προέκυψε ότι το μεγαλύτερο ποσοστό της συνολικής πληροφορίας είναι συγκεντρωμένο στους τρεις πρώτους παράγοντες και για τις 3 υποπεριοχές. Το υδρογράφημα καθενός από τους ανωτέρω παράγοντες παρουσιάζει συγκεκριμένα μορφολογικά χαρακτηριστικά, τα οποία και τον διαφοροποιούν απολύτως από τους υπόλοιπους. Παραδείγματα παρόμοιων χαρακτηριστικών είναι στην περιοχή των Φαρσάλων η εμφάνιση εποχιακών μοτίβων σχήματος ανεστραμμένου “U” και ανεστραμμένου

“V”, στην περιοχή της Καρδίτσας η εμφάνιση διετών κύκλων και στην περιοχή των Τρικάλων η εμφάνιση απότομων πτώσεων στάθμης.

Ακολούθως, τα υδρογραφήματα των γεωτρήσεων για κάθε μια από τις 3 υποπεριοχές τοποθετήθηκαν σε ένα τρισδιάστατο διάγραμμα με συντεταγμένες το ποσοστό συμμετοχής τους σε κάθε μια από τις 3 κύριες συνιστώσες. Έτσι επιτεύχθηκε η σύγκριση των υδρογραφημάτων μεταξύ τους ανάλογα με την εγγύτητά τους στο διάγραμμα. Με βάση τα διαγράμματα αυτά έγινε ομαδοποίηση των γεωτρήσεων σε τρεις ομάδες για κάθε υποπεριοχή. Η κάθε μια από αυτές τις ομάδες μπορεί να χαρακτηριστεί από τη σχετική κυριαρχία ενός μόνο παράγοντα.

Όπως διαπιστώθηκε στη συνέχεια από την τοποθέτηση των γεωτρήσεων στους γεωλογικούς χάρτες, η διαφοροποίηση στις συγκεκριμένες ομάδες αντανακλάται και στη χωρική τους κατανομή. Το γεγονός αυτό διευκολύνει τη φυσική ερμηνεία της συγκεκριμένης ομαδοποίησης βάσει των γεωλογικών χαρακτηριστικών του υπεδάφους, της εγγύτητας με επιφανειακά νερά, της σχετικής θέσης στην πιεζομετρική επιφάνεια καθώς και άλλων φυσικών παραμέτρων. Γενικότερα, τα υδρογραφήματα της κάθε γεώτρησης μαζί με τη στρωματογραφική της στήλη έδωσαν μια πιο ολοκληρωμένη περιγραφή της κάθε περιοχής όσον αφορά το υδρολογικό της καθεστώς, αφού δόθηκε ερμηνεία στην υδραυλική συμπεριφορά της κάθε γεώτρησης και στο κατά πόσο ήταν εύκολο να αναπληρωθεί μια ποσότητα ύδατος μετά από συνεχή άντληση δεδομένης της φύσης των πετρωμάτων.

Με βάση τα ανωτέρω αποτελέσματα είναι δυνατό να προταθεί μείωση των γεωτρήσεων παρακολούθησης σε κάθε περιοχή με στόχο την εξοικονόμηση πόρων. Πιο συγκεκριμένα, στην περιοχή των Φαρσάλων προτείνεται η παρακολούθηση από την πρώτη ομάδα της γεώτρησης LB70 ως πλέον ενδεικτικής, της 540B από τη δεύτερη ομάδα και της SR4 ως ενδεικτικής της τρίτης ομάδας. Όσον αφορά την Καρδίτσα, προτείνεται η γεώτρηση D36 ως ενδεικτική της πρώτης ομάδας, η PZ32 για τη δεύτερη ομάδα και η PZ19a για την τρίτη. Τέλος, στην περιοχή των Τρικάλων, οι γεωτρήσεις TB20, PZ1, PZ17 μπορούν να θεωρηθούν ενδεικτικές για τις τρεις ομάδες αντίστοιχα. Τα υδρογραφήματα των ανωτέρω προτεινόμενων γεωτρήσεων μοιάζουν περισσότερο σχηματικά με τους αντίστοιχους παράγοντες και συμπυκνώνουν τη συμπεριφορά της κάθε ομάδας. Δεδομένης της δύσκολης οικονομικής κατάστασης και της έλλειψης ανθρώπινου δυναμικού, και εφόσον η μείωση του αριθμού των γεωτρήσεων που παρακολουθούνται κριθεί αναγκαία, η παρακολούθηση μόνον των αντιπροσωπευτικών γεωτρήσεων όπως αυτές προτείνονται στην παρούσα εργασία, αποτελεί την ενδεδειγμένη λύση έτσι ώστε να ανακτάται το μεγαλύτερο ποσοστό της πληροφορίας σχετικά με τις διακυμάνσεις και τη γενικότερη συμπεριφορά του υδροφόρου ορίζοντα.

Acknowledgments

The current study entitled: «Interpretation of groundwater hydrographs in the West Thessaly basin, Greece, using Principal Component Analysis», was conducted as the Master Thesis of the Interdisciplinary Programme of Postgraduate Studies “Geoinformatics” of the National Technical University of Athens, during the academic year 2015-2016.

I was motivated to be involved in this study, due to the stimulation from the Geostatistics class that I attended within the master curriculum, where I got familiar with the geostatistics fundamentals. Due to my geologic academic background, the current study provided the chance to broaden my scientific horizons, and develop my skills in a topic very close to my academic interest.

I would like to thank all the people who contributed in the preparation of this study and made this thesis possible.

First and foremost, I would like to thank my supervisor Associate Professor K. Modis for his constant support, patience and guidance throughout my research. I feel indebted to him for the great opportunity that he provided to me during my postgraduate studies and the countless hours of comprehensive discussions we had. I truly believe that without his continuous help and directions in daily basis the completion of this thesis would have been very difficult.

I would also like to thank Assistant Professor K. Adam for her warm encouragement, valuable advices, scientific remarks and optimistic attitude which inspired me. Besides that, I would like to thank her for her painstaking effort in proofreading and editing my paper.

Moreover, I want to express my gratitude to Emeritus Professor I. Koumantakis for his constructive comments, his valuable contribution in this study, especially in the part of hydraulic conditions interpretation and in hydrogeologic rocks’ behavior. The time he dedicated to this study was precious and is greatly appreciated.

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1. Introduction

Measurements of water level in monitoring wells or piezometers consist an integral part of ground water studies. The water level data can be used to plot hydrographs of hydraulic head versus time, which are subsequently used to evaluate the response of the ground water system to either natural or manmade activities over time at the location of that monitoring station. Statistical methods can quantitatively summarize the data collected over space and time during the course of an extensive monitoring program (Modis and Sideri 2015) providing the basis to better understand the various types of water level fluctuation patterns within a study area. Statistical analysis of available water level data can also provide the basis in order to optimize and effectively reduce the number of measuring locations without jeopardizing the accuracy of compiled information in the long-term.

In order to analyze water level data, lower dimensionality and reveal patterns in such large datasets, an analytical procedure is required. Principal Component Analysis (PCA) is intended to establish a series of factorial variables that summarize all the hydrogeochemical information. This is the most widely used method of multivariate data analysis owing to the simplicity of its algebra and its straightforward interpretation. Principal components analysis can be used to summarize the data covariance structure in fewer dimensions of the data. It is used to identify the important components that explain most of the variance of a system. Moreover, it focuses on providing a representation of a multivariate data set using the information that is contained within the covariance matrix, so that the extracted components are mutually uncorrelated. In addition, the principal components have the important property that successive components explain the maximum residual variance of the data in a least squares sense.

This kind of analysis may find several different uses regarding the examination of monitoring wells. According to Francisco Sânchez - Martos et al., when factorial variables, derived from PCA, are defined, the physico - chemical processes that affect groundwater can be identified and subsequent analysis of the spatial distribution of these variables using geostatistical estimation techniques can take place. The geostatistical techniques constitute a useful tool for the study of spatial variability in these hydrogeochemical processes, since they enable the distribution of the variable throughout the aquifer to be analyzed via its estimation and subsequent mapping. PCA can also provide e.g. the degree of salinization, thermal influence or marine intrusion in the water (Pulido Bosch et al. 1992). Furthermore, important geomorphological parameters that contribute to runoff erosion (Hann 1997), or complex hydrogeological conditions such as transmissivity variation (Premchitt and Das Gupta 1981) can be identified through PCA. Finally, the results of the PCA can provide some basic insights into the similarities and dissimilarities in patterns of water-level fluctuations among wells and might be useful in selecting wells for long-term monitoring (Winter et al. 2000).

Such a type of analysis has been performed in this thesis in order to examine the behaviour of various monitoring wells in West Thessaly basin. This basin is the bigger part of the Thessaly plain and the one having the most important and rich aquifers. Its importance is notable, due to the fact that Thessaly basin has high water demands that are covered to a big portion by wells, given the absence of reservoir infrastructure, except from Plastiras and Tavropos dams. This situation has led to overexploitation resulted to the manifestation of land subsidence phenomena (Marinos et al. 1995, 1997) and ground deformations (Modis and Sideri 2014) with extended damages in certain sites (Rozos et al. 2010).

More specifically, the data analyzed in the present study were collected from three research sites in the West Thessaly basin, in Greece (Figure 1). The dataset includes monthly piezometric time series taken from 62 water wells in the period from 1974 to 2014. The goal of the current thesis is to define a few hydrograph patterns that would represent the general patterns of water level fluctuations over a 20- to 23-year period for each site. Furthermore, by determining the extent to which hydrographs at individual well locations relate to the statistically computed hydrographs, the spatial distribution of hydrograph patterns could be mapped throughout the area of each of the three sites. Finally, certain “key” monitoring wells, that would best describe a group of similar wells, will be identified and be characterized as crucial to be monitored and looked after. On the other hand and due to money and resources restraint, fewer wells could be monitored, giving priority to those key wells.

2. Site description

The study area is located in the West Thessaly basin, (Figure 1) subdivided into three subsequent smaller areas. The first area is located in the Farsala region containing the lowland area surrounding Ag. Georgios, Farsala and Stavros villages. The second area is located in the S-SW part of the basin including the wider Karditsa prefecture area containing a lot of semi - rural and urban areas. The third area, Trikala area, includes the largest part of the Western Thessaly basin and is being crossed by Pineios and its major side rivers Pamissos and Portaikos (Figure 3, Figure 6).

Figure 1: Location of the West Thessaly Basin

3. Theoretical Background

3.1 Geomorphological settings

The Thessaly basin is a lowland area in Central Greece (Figure 2) with an overall area of about 4,520 km^2, mainly drained by the Pineios River. The basin is surrounded by the mountains Ossa, Mavrovounio and Pilio to the east, Olympos and Titaros to the north – east, Kamvounia, Chasia and Antichasia to the north and north – west, Pindos to the west and Othrys to the south.

The basin is subdivided by a group of hills -which form an elongated ridge consisted of mountains Zarkos, Titanos, Fylliios and Chaklodonios- in two sub-basins, the Western and the Eastern one. These are mainly individual hydro-geological units, with high potential aquifers: (a) the hilly-mountainous region, with an absolute altitude ranging from 200 m up to more than 2,000 m and (b) the low-land region, with an absolute altitude up to 200 m. These areas occupy 62.12 % and 37.88 % of the overall area, respectively.

Figure 2: Study area (Google earth)

3.2 Climatic and hydro-meteorological characteristics

The climate of the wider study area is considered continental with cold winters, hot summers, and large temperature differences. According to the hydro-meteorological data for a 37 years' time-period (1970-2007), obtained from 14 meteorological stations located in the wider Thessaly region, the following results have been derived: (a) the rainy period begins in October and ends in May, (b) the mean annual precipitation is 885.8 mm, (c) a wide fluctuation of the annual rainfall data is recorded with annual measurements ranging between 541.7 and 1,592.0 mm, (d) an increase in rainfall from E to the W is evidenced, (e) the mean annual temperatures range between 5.0 and 26.6° C, and (f) the annual fluctuation pattern of temperature is exactly the opposite from that of the precipitation.

3.3 Geological structure and tectonics

The Western Thessaly basin lies between the internal and external Hellenides (geotectonic units), which, along with the recent tectonic activity explains the great variety of the prevailing geological formations.

Rock formations that surround the basin are distributed between four geotectonic units of the Alpine orogeny regime.

I. The Metamorphic Pelagonian unit consists of gneisses, crystalline schists, phyllites, crystalline limestones, marbles and dolomites.

II. The Sub - Pelagonian unit consists of schists, schist-gneisses, sandstones, pelites, limestones, dolomites, ophiolites and flysch.

III. The Koziakas unit consists of limestones, conglomerates, sandstones, pelites and flysch.

IV. The Pindos unit consists of limestones, cherts, first flysch sequences and transition to flysch formations beds.

More specifically, the main lithological formations that among all play an important factor in the hydrogeological conditions in the area are:

- Flysch of Central Greece.

This unit consists of shales, siltstones and sandstones in alternate layers. Locally, conglomerates, grits or marls also participate, while calcareous schists and limestones or marly limestones are even more rarely interbedded. This formation is intensely fractured and multifolded. Surface beds show a medium to strong weathering and a dense net of discontinuities, causing intense secondary looseness. In macro-scale, flysch is considered as an impermeable formation, allowing the occurrence of small springs, usually between the fragmentation zones or weathering mantle and bedrock.

Flysch is characterized by an obvious instability, which is usually connected with the numerous heterogeneous layer contacts and the steep bed inclinations, in conjunction with the strong relief and the action of water. Problems connected with the foundations of civil engineering projects, especially regarding road construction projects, are very often. In general, geotechnical behavior presents a clear anisotropy and rapid changes, controlled by the degree of looseness, the orientation of discontinuities, the dip of slopes and the presence and action of water. Landslide phenomena occur with an increased frequency, usually affecting the weathering mantle and the upper fragmentation zone.

- Flysch of Eastern Greece.

This unit consists of shales, siltstones, sandstones, marly limestones, conglomerates or grits and limestones in alternate layers. This formation is often intensely fractured and multifolded and gives a weathering mantle of varying thickness. In general, geotechnical behavior presents a clear anisotropy and rapid changes, controlled by the degree of looseness, the orientation of discontinuities, the dip of slopes and the action of water.

- "Boeotian” flysch

Consists of sandstones, conglomerates, breccias, siltstones, shales, marly limestones, cherts and radiolarites in alternate layers. Locally thin intercalations of ophiolites or limestones are found. The geotechnical behavior presents anisotropy and rapid changes.

- Transition beds of limestones to flysch.

This unit consists of thick-bedded limestones, brecciated limestones, coarse-grained sand-stones, siltstones, schist-marls, marly limestones, marls and cherts. This formation is intensely fractured and multifolded. In general, geotechnical behavior presents a clear anisotropy and rapid changes, controlled by the degree of looseness, the orientation of discontinuities, the dip of slopes and the action of water.

- Upper-Cretaceous limestones of Central Greece with nodules or lenticular silica layers.

This unit consists of thin to medium-bedded limestones, often micro-brecciated, with nodules or lenticular silica layers and locally thin intercalations of shales. The rock mass behavior presents a characteristic anisotropy and non-uniformity and is controlled by the density of chert and schist interbeds. The increased density of discontinuities and the heterogeneous contacts reduce the shear strength and increase the instability on steep slopes. Extended landslide phenomena have been observed in these formations.

- "First" flysch.

Alternations of thin layers of red marls, cherts, marly limestones, coarse-grained sandstones, siltstones and clayey-marly schists, as well with brecciated limestones and conglomerates in the upper members of this series. The intact rock, usually, is characterized by satisfactory geomechanical behavior for the foundation of civil engineering projects.

- Cretaceous limestones of Thymiama.

Limestones thin to medium-bedded or unbedded, usually micro-brecciated. In the upper members of this series, nodules of red cherts and siltstones are observed locally. The breccias are mainly originating from limestones, cherts, ophiolites and siltstones. The foundation requirements for the construction of civil engineering projects are satisfied by the high mechanical strength values of the formation.

- Cretaceous limestones of Eastern Greece.

This unit consists of compact limestones, thin to thick-bedded or unbedded, locally brecciated or crystalline or marly, giving extended talus cones at places. Usually fractured and strongly karstified in the upper beds. The intact rock is characterized by the high values of strength parameters, while the rockmass shows medium to high permeability and satisfactory geomechanical behavior for the foundation of civil engineering projects. Failures are usually observed as e.g. rock falls on steep slopes.

- Jurassic limestones of Koziakas.

This unit consists of medium to thick-bedded limestones, of white or grey colour, oolithic and locally compact or brecciated or karstified. At the formation’s base may appear breccia-conglomerate or conglomerate layers. The intact rock is characterized by satisfactory geomechanical behaviour for the foundation of civil engineering projects.

- Limestones (Cretaceous to Triassic), alternating with cherts, schist-cherts or schist-marly layers.

This unit consists of limestones and thin alternations of cherts, shales, siltstones, marly limestones, marls or silica layers. They are intensively folded and fractured. The geotechnical behavior of the rock mass is mainly determined by the physical condition of the formation and its lithological composition and to a smaller extent by the mechanical parameters of the various phases.

- Shales and cherts (Cretaceous to Triassic).

Thin alternations of shales and cherts with scattered thin-bedded limestones, sandstones and siltstones. They are intensively fractured and multifolded. The mechanical behaviour of the rockmass on the slopes is characterized by low shear strength but, in gently inclined areas, the compression strength is satisfactory. Landslide phenomena mainly occur in the thick weathering mantle and the fractured zone.

- Basic and ultrabasic igneous rocks - ophiolites.

Ophiolites, peridotites, serpentinized peridotites, pyroxenites, dunites, diabases, dolerites, basalts, diorites, gabbroes, granites, etc. In the upper parts they are strongly altered and weathered, covered by thick mantle. They are impermeable, but the intensively fractured zones present increased permeability. The values of their mechanical parameters are definitely influenced by the natural state of the rock mass (degree of alteration-weathering and fracturing density).

- Semi-metamorphic rocks.

Phyllites in alternating layers of schists, sandstones, quartzites and thin red limestones. These formations in unweathered state, especially those rich in silica and calcitic elements, exhibit high mechanical strengths and satisfactory geomechanical behavior.

- Crystalline limestones-marbles.

This unit consists of micro or coarse-crystalline limestones-marbles, often of great thickness and extended surface development in the areas of metamorphic masses. These are compact, medium to thick-bedded rock, homogeneous and highly permeable. They present high strength parameters and good behavior as foundations of civil engineering projects.

- Metamorphic rocks.

This formation consists of gneisses, mica-amphiboles and other schists, quartzites and amphibolites with frequent marble and cipolin interbeds. Locally, phylites in alternating layers of schists, sandstones, quartzites and thin red limestones. They are impermeable formations with perfect schistosity and great thickness, characteristic homogeneity and satisfactory uniform behavior in static and dynamic loadings. In unweathered state, they present high strength parameters.

Post-Alpine formations that also contribute to the geological structure of the Thessaly basin consist of:

(a) Molassic formations of the Mesohellenic trench

i. Mainly coarse-grained formations: conglomerates, breccias or grits, with intercalations of sandstones and marls.

ii. Mainly fine-grained formations: (a) marls or silty marls or clayey- marls, with intercalations of sandstones and conglomerates or grits, (b) marls or silty marls and (c) marls or clayey-marls or silty marls, with sandstones and limestones in thin, mainly, layers.

(b) Neogene sediments (clays, silts, marls, sands, sandstones, conglomerates, breccias, grits and marly limestones)

Neogene sediments.

This unit consists of clays, silts, marls, clayey-marls, sands, sandstones, marly sandstones, conglomerates, breccias, grits and marly limestones, mainly occur in thin layers. The hetero-geneity, but mainly the lateral evolution and wedging out of the horizons, contribute to the non-uniform and anisotropic behaviour of the formation as a whole, and to the rapid change of the mechanical parameters in the different horizons, both vertically and laterally.

(c) Quaternary deposits (alluvial and fluvial deposits, fluvial terraces, screes and talus cones).

i. Fluvial-stream deposits.

   This unit consists of cobbles, pebbles, gravels, grits and sands with ranging, but usually low proportions of clayey silts to sandy clays. They are loose deposits in alternate layers, with rapid wedging out.

ii. Fluvial terraces.

   This unit consists of cobbles, pebbles and gravels of various size and origin, with sands, sandy silts, clayey silts or marls at places. Locally, cohesive conglomerates in banks with red clayey cement are present. In general, their geomechanical behaviour is usually controlled by the characteristics and percentage of the fine material.

iii. Screes and talus cones

This unit consists of pebbles, cobbles, gravels of different origin and various sizes and small fragments of limestones, with sandy-clay materials, constitute them. Grits, sands, clayey silts or sandy silts also participate at places.

The major part of the Western Thessaly basin is comprised mainly of formations of Quaternary age (2,570.62 km^2, or 42.19 %). Their thickness exceeds 550 m and there is a progressive transition from deposits formed within a lacustrine environment to the more recent fluvial deposits.

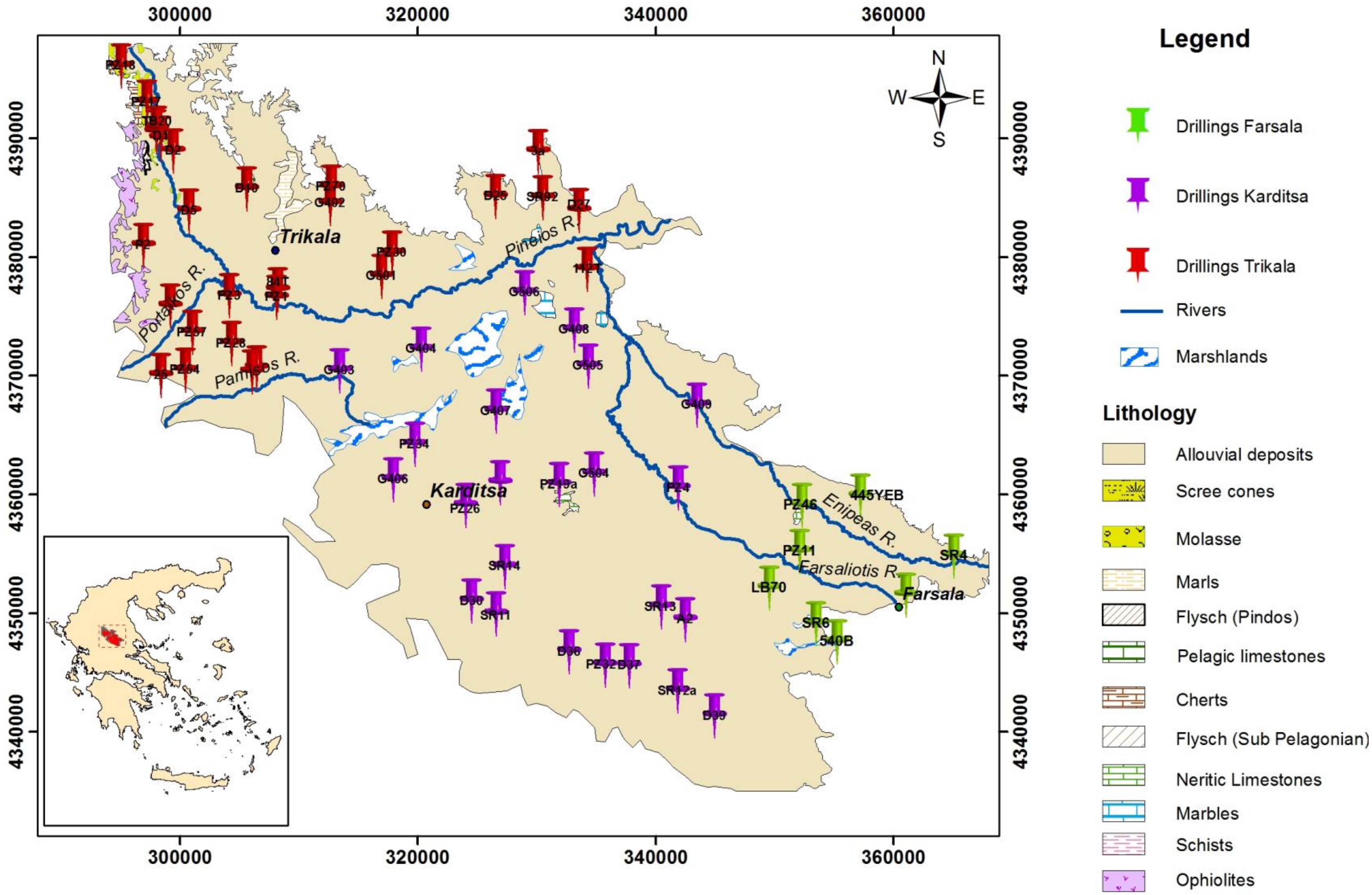


Figure 3: Geological map of the West Thessaly basin.

Referring to the tectonic evolution of the wider area, two extensional events took place near the end of the final phase of Alpine-related folding; the one with NE-SW directed extension (Miocene-Pliocene) and the other with N-S directed extension (Lower-Middle Pleistocene until now). The latter event is responsible for the significant seismic activity that exists in Thessaly.

The heterogeneity of the phases results to a strong non-uniformity and anisotropy in the engineering behavior of the mixed formations, with mechanical parameters which differ significantly in the various horizons according to the lithological composition and physical state of the formation. Therefore, sandstones, marls and conglomerates usually present high values in both shear and compressive strength, while sands and clays present wide fluctuation in the values of their mechanical parameters. Landslide phenomena are limited in the weathered horizons of the fine-grained phase. Rock falls can be observed in the cohesive conglomerates.

3.4 Hydrogeological conditions

The Quaternary deposits encountered in the basin contain the main aquifers of the study area. These aquifers constitute a system of unconfined shallow aquifers, extending through the upper layers, and successive confined-artesian aquifers developing in the deeper permeable layers. This system is supplied by water flowing through the lateral infiltration zones and originating from the karstic aquifers in the alpine carbonate formations, outcropping in the boundaries of the Western Thessaly basin, as well as from infiltrated surface water. The majority of the aquifers in the Thessaly plain are under a regime of overexploitation, resulting in a systematic drawdown of the groundwater level.

The richest aquifers of the Thessaly water district are developed in the Western Thessaly basin. This occurs due to the groundwater supply from the infiltration of river surface water that emit in the basin, through the alluvium cones that have been formed.

For this reason, the aquifers can be classified depending on the main branch of the hydrographic network as follows (Kallergis 1970, Sogreah 1974, Constantinidis 1978):

Pineios – Portaikos – Pamissos cone, in the west – northwest part of the plain, with a high resources aquifer, which is being supplied by both the infiltration of the three rivers and that of the rainfall, while one part of them returns to the surface through alluvial springs. The total supply rises 600 × 106 m^3/year, while the 520 × 106 m^3/year is due to the rivers' infiltration (Sogreah, 1974). The presence of these springs occurs due to the fact that the water transportation to deeper level becomes very difficult because of the low conductivity of the alluvial deposits in contact. This is a common phenomenon even when overexploitation of the aquifers happens.

Sofaditis' cone, in the homonym river, with a high resources drain aquifer, approximately 26 × 106 m^3/year (Ministry of Agriculture, 1989) swings to an under pressure aquifer and is being supplied by the river infiltration. This happens due to the lithology of water basin supply (ophiolites, flysch), where the conglomerates and the gravels are being interrupted easily by clayey material and their participation becomes more intense as the cone is expanding to the lowland.

The rest of the western plain is characterized by the alternation of pervious and impervious deposits leading to the formation of simultaneous under pressure aquifers. Usually in a depth of 10 – 30 m from the surface, there is a layer of clay that isolates the pervious horizons of the deposits, making them under pressure. They are mainly supplied by the Pineios affluents' cones with slow rate, action that makes the water replacement very difficult.

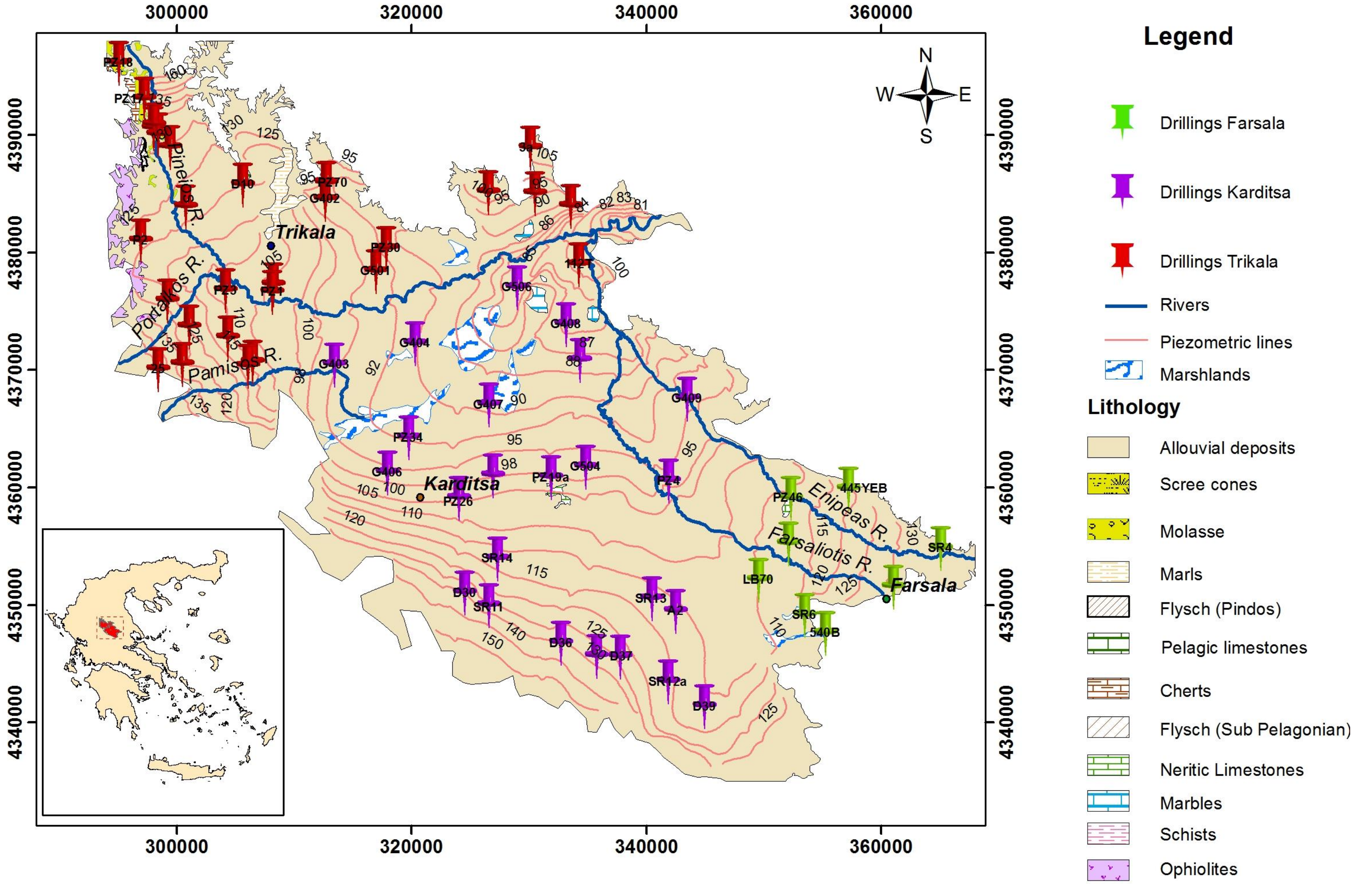


Figure 4: Geological and piezometric map of the West Thessaly basin.

Thessaly water district, in which the majority of water is used in irrigation, is currently one of the most deficit in water district of Greek mainland (Koutsogiannis et al. 2008)**.** The main water resources are Pineios River and its underground aquifer in both western and eastern Thessaly. The lack of infrastructure in dams, combined with the continuous farming, has led to a substantial drop in the river flow during summer and in a dramatic degradation of the aquifers, due to the intensive use of water abstraction drillings. Also the problem has deteriorated by using earthy channels for the moving the water leading to high losses in water.

Unfortunately, the overexploitation of the aquifers in the Western sub-basin during the last decades, led to the manifestation of land surface subsidence phenomena related with extended damages observed in certain sites. Namely in the area extending from Farsala to Stavros towns, seen in Figure 3, uncontrolled groundwater abstraction used for irrigation resulted in extensive land subsidence recorded since 1990 (Marinos et al. 1995; 1997).

An excessive drawdown of the groundwater table (in the range of 20 - 40 m) has been recorded in the various successive aquifers the last decades. The study area consists of terrestrial Pleistocene deposits containing sands and gravels interbedded with clayey silt to silty clay horizons. The overexploitation of groundwater activates the subsidence mechanism in the discharged aquifers and subsequently leads to the manifestation of the accompanying phenomena on the surface, apart from the land depression. In the center of the town of Farsala, an area extending 50 m x 360 m, was intensively damaged by land surface subsidence phenomena. The road pavements present multiple fractures, reactivated after any repairing work. Several buildings were structurally affected by the occurrence of ruptures and were intensively damaged, requiring expensive repairing or reconstruction works. Small ground ruptures have also been observed in the northern part of the town, in an area covering 180 m x 200 m. Beyond the south western limits of the town and at the west of the railway line, two more extensive ruptures were observed, with total length 1,0 m and 2,500 m respectively. The northern one has a mean azimuth of about 100° and shows a vertical displacement at a range of 20 to 50 cm. The southern rupture, with a mean azimuth of about 110°, presents a vertical displacement of 15 to 150 cm (Apostolidis and Georgiou, 2007).

In addition, in the town of Stavros, the main ground rupture was found to the west of the railway line. This tensile rupture has a total length of about 2,100 m, an azimuth of 105° and a vertical displacement 60 cm. The rupture affects road pavements and numerous buildings. The buildings founded along the trace of the ruptures show a considerable degree of damage, such as cracks in the stonework, distortions in doors, windows, stockyards and pavements (Figure 5). In addition, several ground ruptures are located in the south of the town, intersecting cultivated areas. The study of these phenomena can provide very useful information to be used in the process of urban and regional land use planning in the study area and not only (Rozos et al. 2010).

Figure 5: Damages due to land subsidence in West Thessaly basin. The cracks in the stonework on the left photo by Apostolidis and Georgiou (2007) evolve, despite the repairs even eight years after, as seen in the right photo taken by the author in 2015.

Given, the significant adverse impacts stemming from the uncontrolled exploitation of ground waters in the Thessaly basin, including both depletion of the aquifers and extensive land subsidence phenomena, it was concluded that the systematic monitoring of the water levels and the inflows of Pineios River and its affluents is a necessary measure for the reliable assessment of the district's water potential, both ground and underground and to take the necessary management measures.

4. Dataset

Throughout the Western Thessaly basin, several water wells were drilled during the last decades, in order to examine the hydrogeology of the area (Kallergis et al. 1973; Sogreah S.A. 1974) and to monitor the long term variations of ground water levels in an area where intense water abstraction takes place for the irrigation of agricultural areas. The data compiled consist of discrete measurements of the water level in monitoring wells over a period of 22 years (April 1993 to August 2014) for the Farsala area, 20 years (July 1974 to November 1993) for the Karditsa area and 23 years (April 1983 to June 2005) for the Trikala area. Measurements at all sites were taken on a monthly basis. A part of the above mentioned data were acquired by in situ measuring from the author during the summer of 2015. The rest of them, dating back from 1974, were kindly provided from the Water Resources Agency of Thessaly, which is a part of the Decentralized Administration Agency of Thessaly – Central Greece.

The number of wells used for this study was 8 for the Farsala area, 24 for the Karditsa area and 30 for the Trikala area. A minimum of 240 water level measurements were made at each well during the study period. From the monitoring wells present in this area, only the wells with complete records over the period examined were included in the present study since the Principal Component Analytical method requires a full matrix of data. The full matrix requirement consist a constraint for using this statistical method. However, small adjustments to the data set can sometimes be justified. For example, if a few wells are not measured on a given month, these data can be filled using statistical interpolation via SPSS Statistics 23 and Minitab 17 programs.

A Digital Terrain Model (DTM) of the study area, with the location of the monitoring wells examined is given in Figure 6. As shown in this model, the three sites analyzed in the present study are located in lowlands of similar elevations, allowing thus the interpretation and comparison of available ground water level data. The DTM was designed through ArcScene, embedded program of ArcGIS 10.1.

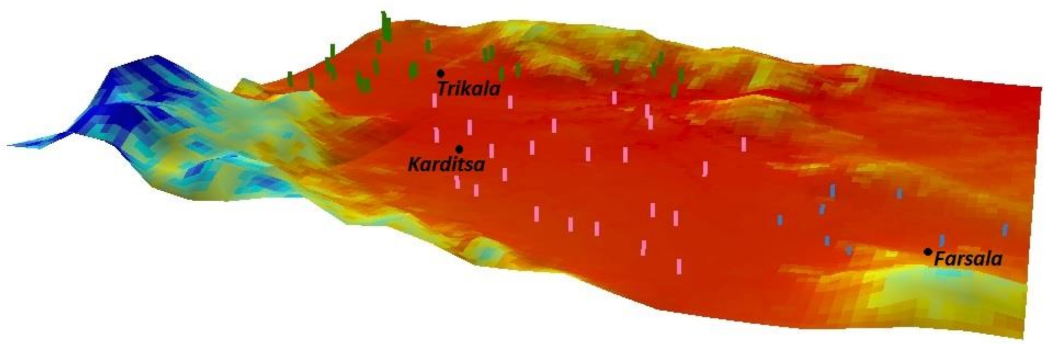


Figure 6: DTM of West Thessaly basin showing the classification of data in three groups according to topography.

Apart from the drilling data, topographic maps scaled 1:50000 from the Geographic Military Service were used, in order to delimit the study area (Figure 7). Moreover, the maps of Institute of Geology and Mineral Exploration [IGME] (Kalampaka, Trikala, Farkadon, Mouzakion, Karditsa, Sofades, Farsala, Fournas, Leontarion, and Domokos) were used as background maps in order to identify and map the lithological formations, rock types, faults, rivers and major cities (Figure 3 and Figure 4). This procedure was carried out using ArcGIS software.

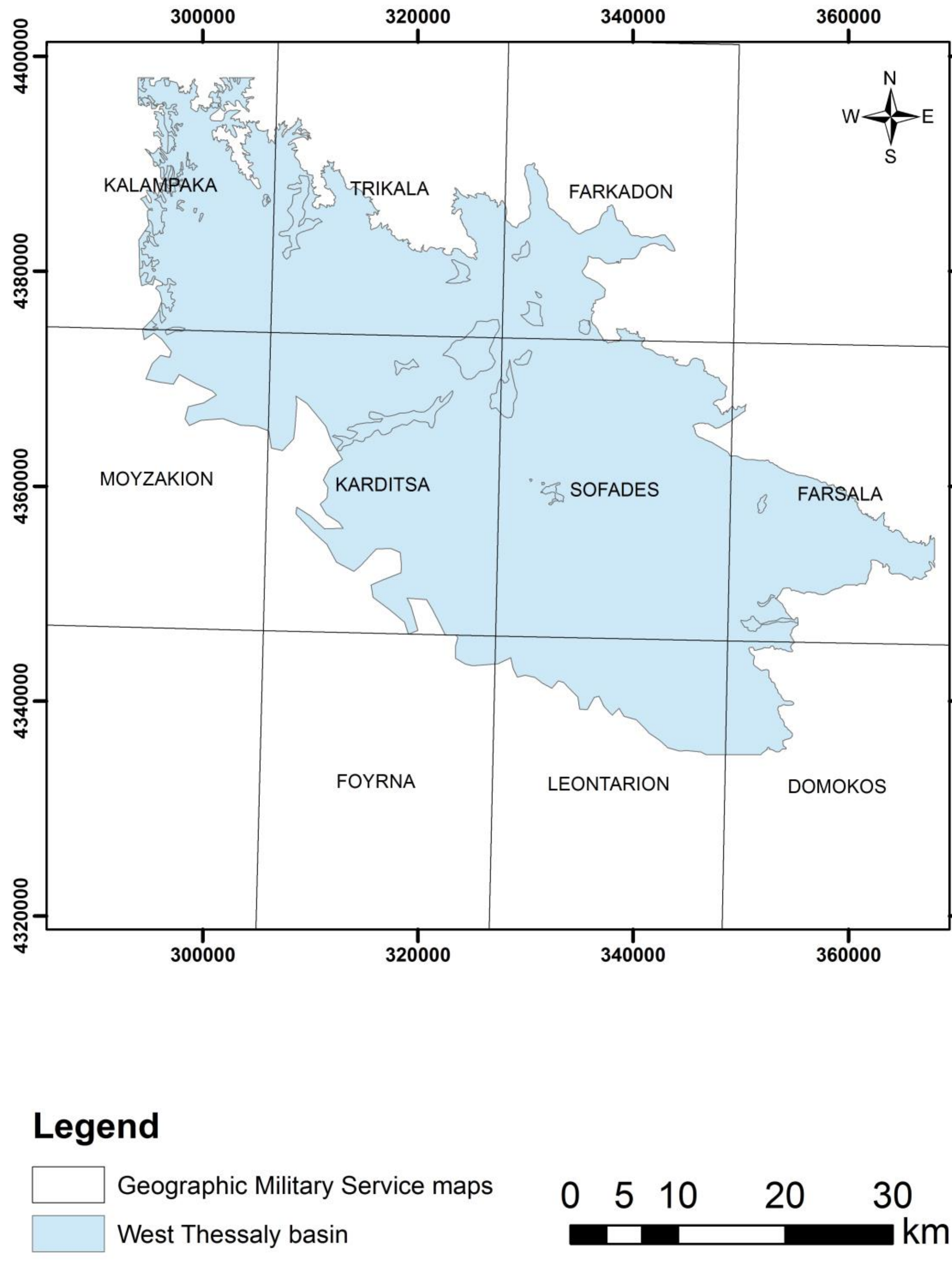


Figure 7: Geographic Military Service maps of West Thessaly basin.

5. Methods

PCA is used in order to reveal temporal patterns in the available water level data. The aim of this method is to determine a few uncorrelated linear combinations of the original hydrographs that can then be used to summarize the data set without losing much information. PCA is a statistical procedure that uses an orthogonal transformation to convert a set of observations / measurements of possibly correlated variables into a set of values of linearly uncorrelated variables called Principal Components. The number of Principal Components is generally less than or equal to the number of original variables.

PCA quantifies the relationship between variables by computing the covariance matrix for the entire data set. The original data matrix is then decomposed into a scores matrix and a loadings matrix (Figure 8) by calculating the eigenvectors and eigenvalues of the covariance matrix. The scores are a measure of the temporal similarity between the observed pattern of water levels for a given date and each principal component. The loadings matrix contains the projections of the original variables to the principal components axes and thus can be visualized as a measure of spatial similarity between the variation of water level variables and each principal component.

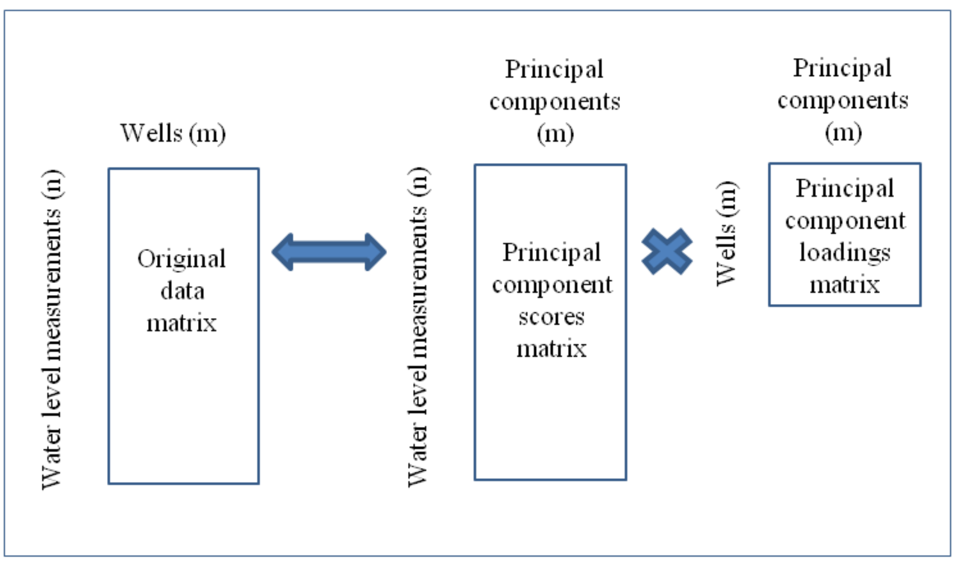


Figure 8: Schematic diagram of PCA transformation of water level measurements (modified from Winter 2000).

Furthermore, another outcome of PCA is that, by plotting the random variables as vectors in their new subspace spanned by the Principal Components, it is possible to examine their cross-correlations and locate potential groups that may share similar characteristics. This ability is extensively used hereafter in order to determine a few hydrograph patterns that would describe the general patterns of groundwater level fluctuations over a 20- to 23- year period for each study area.

The identification of characteristic modes of water level variation occurs through determining which geometric form, represented by the vector e, has the greatest resemblance to all the water level vectors f simultaneously. Averaging across all f, this is accomplished by maximizing the quantity

$$(e^T F)^2 \tag{1}$$

subject to the condition

$$e^T e = 1 \tag{2}$$

where e is an M-component vector representing the geometric form sought and T denotes the transpose. Maximization of Equation 1 is equivalent to maximizing

$$e^T S e \tag{3}$$

where S is the covariance or correlation matrix

$$S = F^T F/N \tag{4}$$

Applying a Lagrange multiplier, λ, maximization of Equation 1 under the unit length constraint (Equation 2) corresponds to the unconditional maximization of

$$eTSe - \lambda e^T e \tag{5}$$

which, when differentiated, yields

$$(S - \lambda I))e = 0 \tag{6}$$

where I is the identity matrix equivalent in order to M, as the solution for vector e containing maximal resemblance to all water level measurements.

Solving for Equation 5 results in a set of eigenvalues, λ_k (k = 1, M), which can be placed as the elements in a diagonal matrix Λ, and a corresponding set of vectors, e_i (i = 1, M), which can be collected as columns into a matrix of principal components (E), for the covariance matrix (S). By arranging the λ_k in descending order, the corresponding principal components represent the geometric forms successively containing the highest resemblance to all water level observations, provided that each component is uncorrelated with all previously calculated components. Each eigenvalue represents the variance explained by its associated principal component. The variance explained by the first three principal components for each of the four sites is shown in Table 1.

The final step in the procedure is to identify systematic patterns of spatial and temporal variability in the original water level matrix.

This is accomplished by calculating the component loadings and scores that reflect the underlying covariance or correlation structure of the data. That structure is inherent in the eigenvectors (e), calculated from either the covariance or correlation matrix, which are the basis of both loadings and scores.

Component loadings can be visualized as a measure of spatial similarity between the water level variables and each principal component. This similarity is expressed as a weighted relationship provided by the product of the matrices E and Λ such that

$$l_{ik}=e_{ik}\lambda_{ik}^{1/2} \qquad (7)$$

where l_{ik} is the loading of the kth principal component on the ith water level variable (i.e., the correlation coefficient between the kth component and the ith variable). For the complete set of variables and components, Equation 6 becomes

$$L = E\Lambda^{1/2} \qquad (8)$$

and L is termed the matrix of component loadings.

Component scores are a measure of the temporal similarity between the observed pattern of water levels for a given date and each principal component. Component scores are computed as the inner product between a water level observation and a principal component:

$$c_{in} = e_i^T f_n \qquad (9)$$

where c_{in} is the score of the nth observation on the i^{th} principal component. For all observations and components, Equation 8 becomes

$$C = E^T F \qquad (10)$$

and C is termed the matrix of component scores. The scores on any individual principal component will have a mean of zero, a standard deviation equal to the component’s eigenvalue, and will be uncorrelated with the scores of all other components.

Principal Component Analysis finds a lot of uses and solves several problems regarding the ground water monitoring. More specifically, the results of the PCA provide some basic insights into the similarities and dissimilarities in patterns of water-level fluctuations among the wells and might be useful in selecting wells for long-term monitoring (Winter et al., 2000). Information provided by the previously described type of analysis may lead to reductions in the number of monitoring wells in some areas. This way, the savings can be used to establish additional monitoring wells in areas with less adequate coverage, to increase the frequency of measurement, or to otherwise upgrade the network.

Another principal objective of the PCA is the study of the hydro geochemical evolution of a complex aquifer, using a methodology that takes into account all the factors, considering the physico - chemical characteristics of the groundwater (temperature, ions concentration, pH, etc.) as well as basic data. Based on this multivariate and complex information, using principal component analysis (PCA), it is intended to establish a series of factorial variables that summarize all the hydro geochemical information. A geostatistical study of these derived variables allows one to work in a reduced multivariate space, and to establish their spatial distribution throughout the aquifer by the calculation of variograms. Likewise, it is intended to produce maps of groundwater quality using these factorial variables and ordinary kriging. In this way, it is hoped to verify whether these new variables permit location of the zones where various physico - chemical processes are superimposed, considering the hydro geochemical and geological parameters. Ultimately, the aim is to identify the development in space of the principal processes that act on groundwater quality.

Namely, the PCA is used with the objective of establishing the associations between the physico - chemical variables of the waters and to note any correlations between them. After performing the primary component analysis, three factorial components can be selected, explaining this way the vast majority of the variance in both analyses (Francisco Sânchez-Martos et al, 2001).

More specifically, by applying PCA, three factors can be defined. They are associated with the principal processes that affect three completely different and uncorrelated factors, for example, the degree of salinization of the water caused by saline enrichment due to flushing of evaporite sediments, thermal influence and marine intrusion, respectively. (Pulido Bosch et al. 1992).

Finally, principal component analysis can be used in surface water hydrology to identify the important geomorphological parameters that contribute to runoff from a catchment (Hann 1977). To evaluate a ground water level monitoring network, the principal component analysis is used to discriminate against the value of information collected from monitoring wells. Thus facing budget constraints in the near future, a manager for a municipality can prioritize sampling from the monitoring network of the aquifer. The management authority can choose to continue monitoring the wells that capture most of the dynamic variation in the aquifer.

Since principal component analysis is based on correlation analysis, it is necessary to ensure that only correlations with physical significance are included in this analysis. The search radius provides a means to identify, approximately, the neighboring subset of wells that have correlated observations. This correlation is associated with the complex hydrogeological conditions (Premchitt and Das Gupta, 1981), e.g., transmissivity variation, in the particular area. Although one may find some correlation between yearly hydraulic head changes among remotely distant wells, say wells 100 km apart, this correlation can be purely coincidental and cannot be interpreted based on the dynamics of fluid flow. Intuitively and obviously, wells that are close to each other will be more correlated than those farther away. This notion is fundamental in the stochastic theories of subsurface hydrology. It is therefore essential to establish a distance within which head values are correlated and the search radius is an essential part of the present method.

On the other hand there are a lot of questions that PCA cannot answer and demand a more thorough and specified geostastical analysis method. Such questions can be “can one improve the prediction by adding observations from non-principal wells into regression? In other words can the additional water level observations from nonprincipal wells improve the prediction?”, or “How many wells should one choose?” (Gangopadhyay Subhrendu et al. 2001)

6. Results and Discussion

Principal component analysis was selected for this study given that an unbiased and efficient tool was sought that would facilitate analysis of the thousands of water level measurements compiled within the monitoring program conducted in the areas under study. The goal was to determine a few hydrograph patterns that would describe the general patterns of water level fluctuations over a 20- to 23-year period for each site. Furthermore, by determining the extent to which hydrographs at individual well locations relate to the statistically computed hydrographs, the spatial distribution of hydrograph patterns could be mapped throughout the area of each of the three sites. As reported in previous studies, (Winter et al 2000) this type of information would be useful in understanding the response of the ground water system to natural processes, such as the distribution of recharge, human activities, such as ground water abstraction for irrigation, as well as indicating the relationship of water level fluctuations to contrasts in permeability of the geologic units.

Analysis of the monitoring data of the three areas under study and their variance versus the principal components are seen in Table 1. As seen in the Table the sum of percentage variance explained by the first three Principal Components varies for the three areas, with Farsala presenting the higher percentage sum. However, it should also be noted that the sum of percentage variance is inversely related to the number of monitoring wells analyzed for each of the three areas under study, i.e. the greater the number of monitoring wells the most difficult to express the percentage variance of available data in only three Principal Components

Principal Components	**1**	**2**	**3**	**Total**
Farsala (Number of wells examined: 8)	73	13	10	96
Karditsa (Number of wells examined: 24)	78	5	4	87
Trikala (Number of wells examined: 30)	65	8	6	79

Table 1: Percentage of variance explained by the first three Components.

6.1 Farsala Area

For the Farsala area, the monitoring data analyzed in the present study were the ones collected from eight wells during a period 23 years. For these data the first principal component (Farsala –Principal Component 1, FA - PC1) accounted for 73% of the variance in the water level data (Table 1). A hydrograph of component scores related to FA-PC1, which is a graphical representation of this variance in the data, is shown in Figure 9a. Hydrographs as this one are referred to herein as scores hydrographs. The second principal component (FA - PC2) accounted for 13% of the variance in the water level data (Table 1). A scores hydrograph for FA - PC2 is shown in Figure 9b. The third principal component (FA - PC3) accounted for 10% of the variance in the water level data (Table 1 and the respective scores hydrograph for FA - PC3 is shown in Figure 9c.

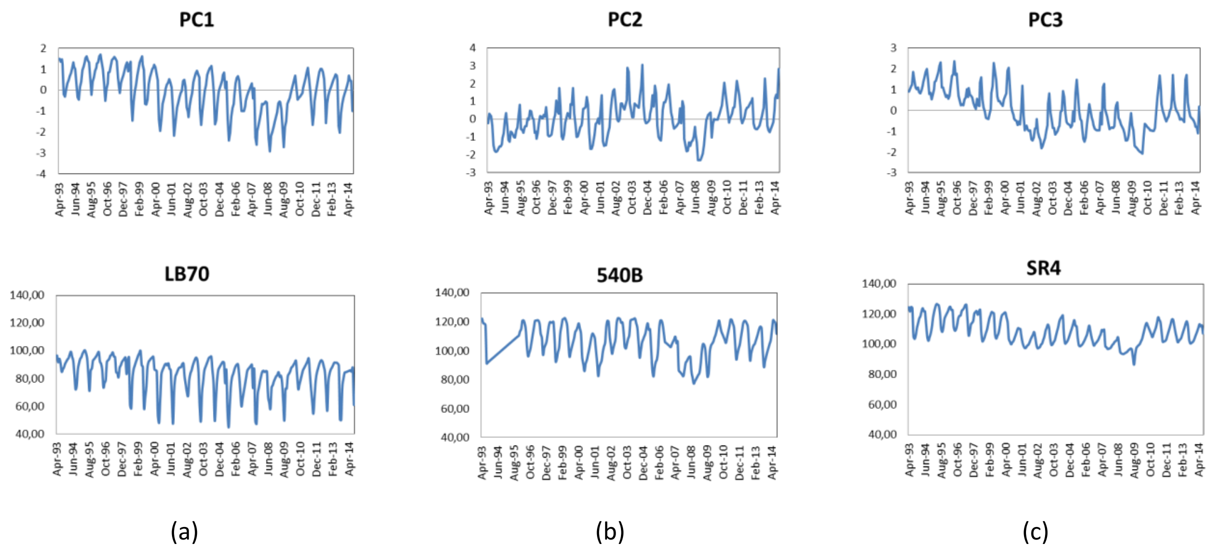


Figure 9: Component scores plot and hydrographs of representative monitoring wells for the three principal components in Farsala area.

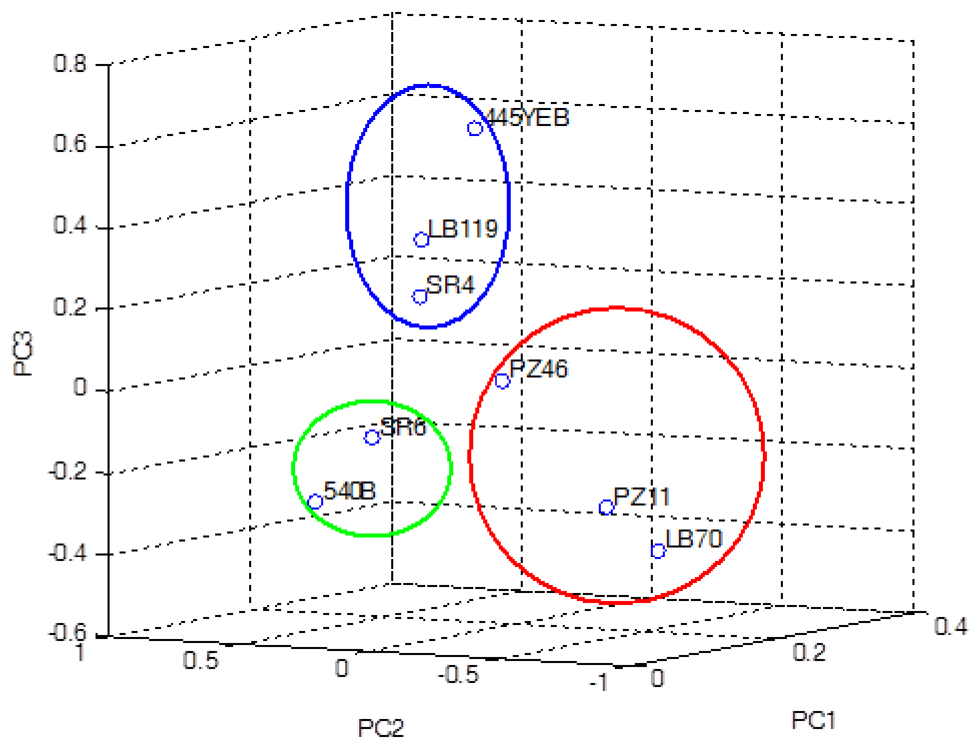


Figure 10: Plot of component loadings for each well in Farsala related to the three principal components.

A plot of the component loadings for each well as they relate to FA – PC1 versus FA - PC2 and FA - PC3 (Figure 10) indicates that for the Farsala area the monitoring wells can be classified in three groups. Wells LB70, PZ11 and PZ46 that present high loadings on FA – PC1 and low loadings on FA - PC2 and FA - PC3 on the lower right side of the diagram are designated as group 1.

Hydrographs on this well group of actual water levels for one of these wells, i.e. LB70 (Figure 9a) clearly reveals the close relationship of these actual hydrograph patterns to the scores hydrograph for FA – PC1 (Figure 9a). Hydrographs show an inverse U-shaped seasonal pattern, reflecting smooth water discharge conditions in the monitored aquifers. A representative hygrograph of monitoring well LB70 for one hydrological year, 2005- 2006, is given in Figure 11.

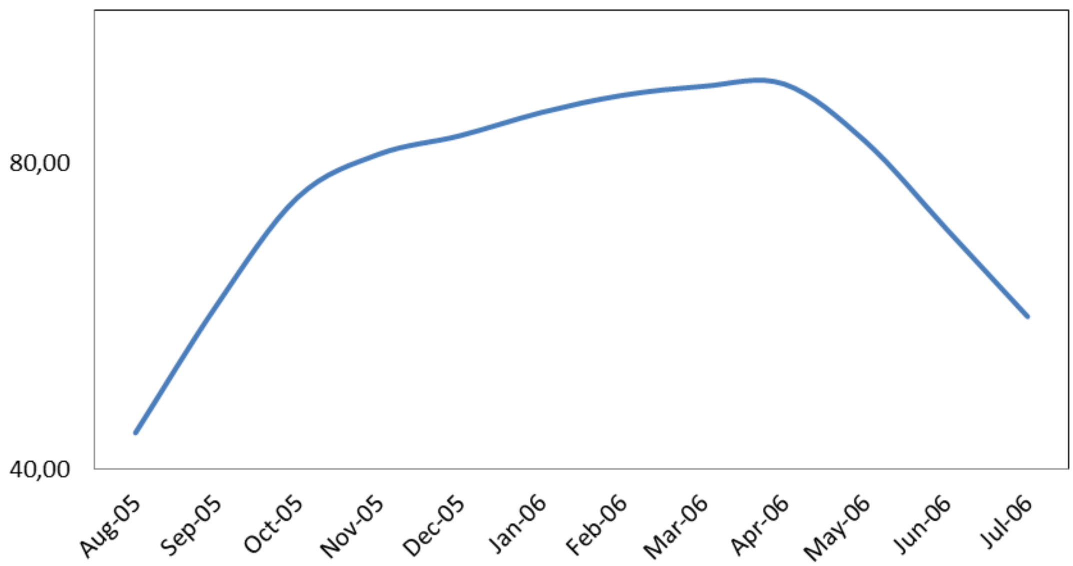


Figure 11: Inverse U-shaped annual pattern of drilling LB70

At the other extreme, wells 540B and SR6 that have high loadings on FA - PC2 and low loadings on FA – PC1 and FA - PC3 seen on the upper left side of the diagram (Figure 10) are designated as group 2. A hydrograph of actual water levels in one of these wells, i.e. 540B (Figure 9b) indicates the close similarity of this hydrograph pattern to the scores hydrograph for FA-PC2 (Figure 9b). In contrast to the first group, they show more flashy and abrupt seasonal patterns indicating a quick respond to recharge. Concerning long term response, they present a 10 year rise trend before stabilizing, suggesting that in this area water abstraction remains lower or is balanced with the recharge of the aquifer. A representative hygrograph of monitoring well SR6 for one hydrological year, 2005- 2006, is given in Figure 12.

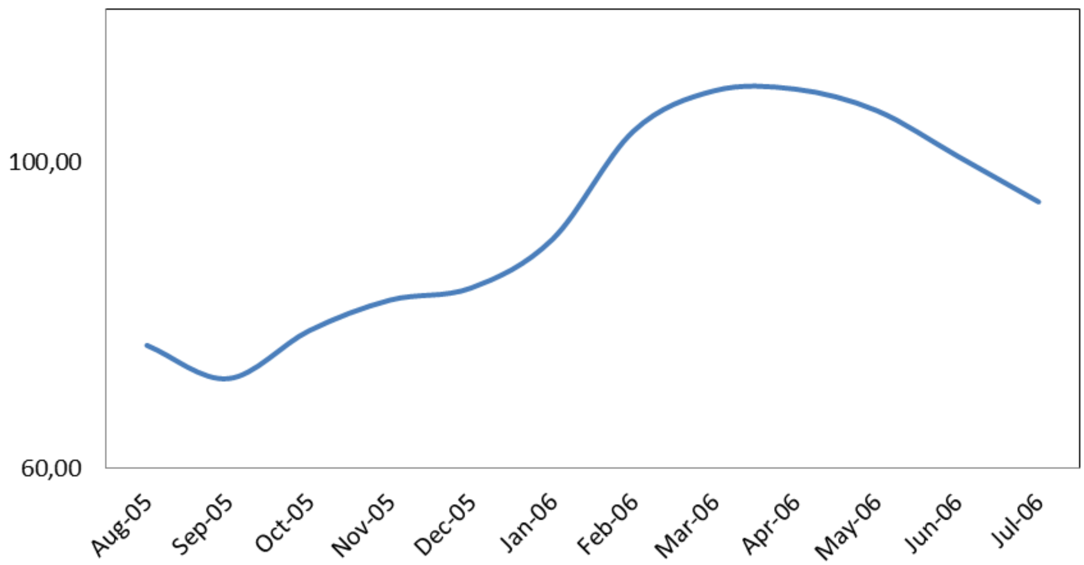


Figure 12: Flashy seasonal pattern of drilling SR6

A third group consists of wells 445YEB, LB119 and SR4 having relatively high loadings on FA - PC3 and moderately high loadings on FA - PC1 and FA - PC2. Hydrographs of actual water levels for one of these wells, i.e. SR4 (Figure 9c) indicate some similarity with the characteristics of the scores hydrographs for FA - PC3 (Figure 9c). In fact, they show a similar type of seasonal response with that of the second group. Nevertheless, as far as long term variations are concerned, they follow a similar trend to group 1, with a 10 year drop first and followed by a rather stable period. A representative hygrograph of monitoring well LB119 for one hydrological year, 2005- 2006, is given in Figure 13.

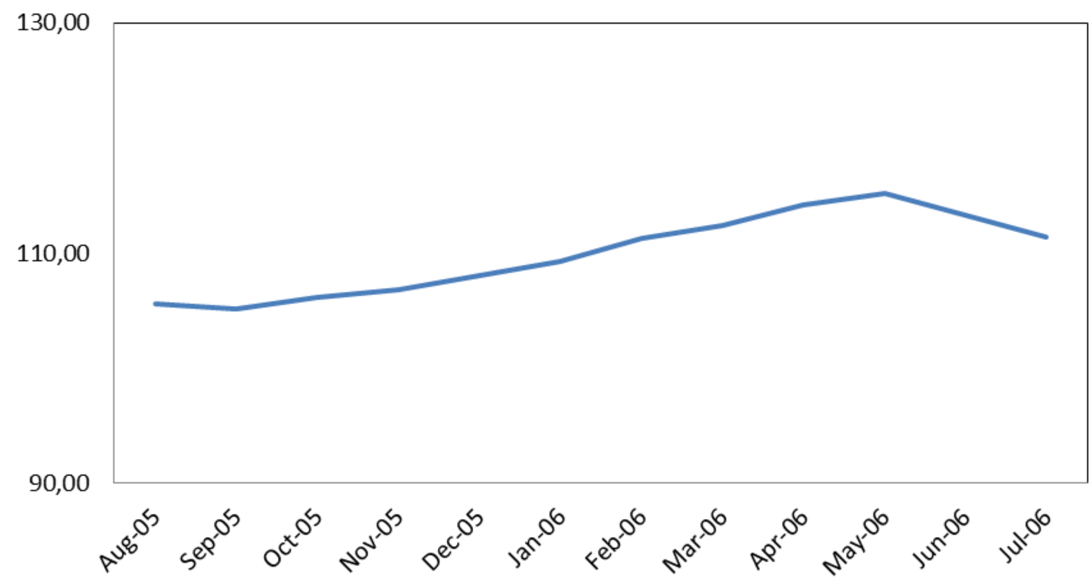


Figure 13: Flashy seasonal pattern of drilling LB119

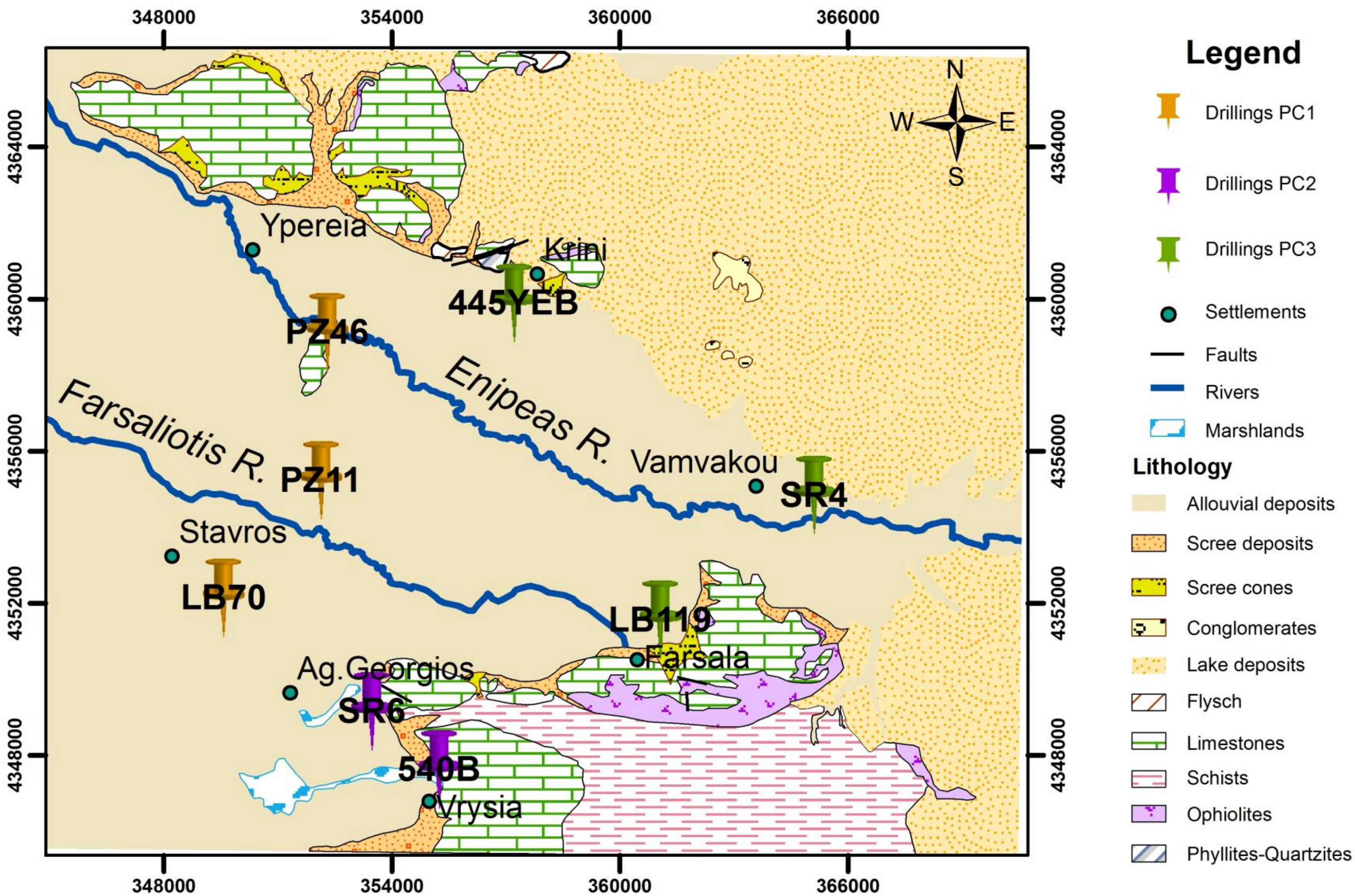


Figure 14: Configuration of the geological formation on the land surface and areal distribution of well groups in Farsala area.

To further interpret the variation of water level variation in the Farsala area, Figure 14, presenting the well groups location in relation with the major geological formations encountered in these locations can be used to develop insight into the causes of the actual hydrograph patterns. For example, as shown in Figure 14, in group 1 wells the monitored water table is located in alluvial formations, where lower hydraulic conductivity results to slower recharge rates. Additionally, these wells are found downgradient of Farsala watershed. Due to the above conditions, water table fluctuations reflect more seasonal and longer-term recharge conditions. In contrast, groups 2 and 3 are found upgradient of Farsala watershed and near the surface recharge zone which is developed within limestones. As a result, in these wells water table fluctuations are abrupt and they respond quickly to aquifer recharge. Groundwater recharge is seen to generally balance or in periods exceed water abstraction for potable water and irrigation as suggested by the long term trend of water level variation. Finally, the difference in long term behaviour between group 2 and the other two groups might be attributed to its vicinity to wetlands, as indicated in Figure 14, and the hydraulic connection of the monitored aquifer with other water bodies encountered within the neighboring carsts.

6.2 Karditsa Area

For the Karditsa area the data set of 24 wells monitored for 20 years were analyzed. For this area, the first principal component (Karditsa - Principal Component 1, KA - PC1) accounted for 78% of the variance in the water level data (Table 1). A scores hydrograph for KA-PC1 is shown in Figure 15a. The second and third principal component (KA - PC2), (KA - PC3) accounted for 5% and 4%, respectively of the variance in the water level data (Table 1). A scores hydrograph for KA - PC2 and KA - PC3 are shown in Figure 15b and Figure 15c respectively.

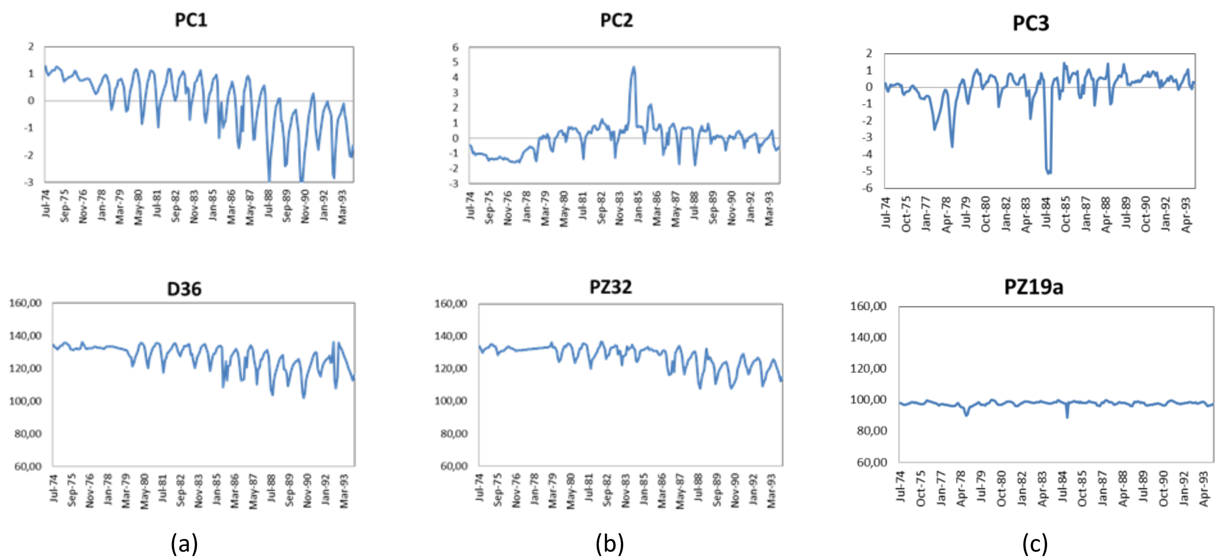
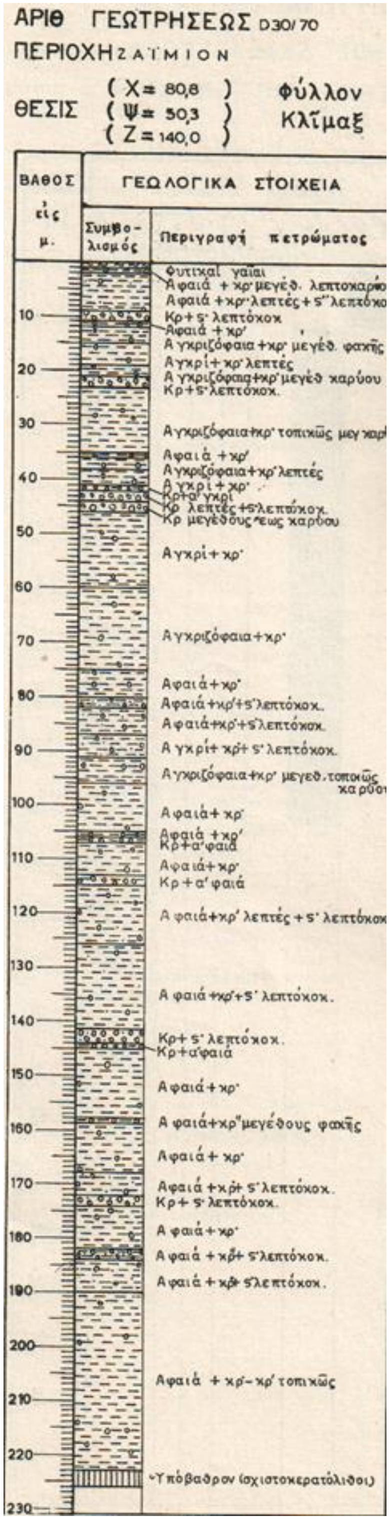


Figure 15: Component scores plot and hydrographs of representative monitoring wells for the three principal components in Karditsa.

A plot of the component loadings for each well as they relate to KA – PC1 versus KA - PC2 and KA - PC3 (Figure 22) indicates that in the Karditsa area also most of the wells fall into three groups. Wells A2, D30, D36 and SR13 that present high loadings on KA - PC1 and low loadings on KA - PC2 and KA - PC3 on the lower right side of the diagram are designated as group 1. Hydrographs of actual water levels for one of these wells, i.e. D36 (Figure 15a) indicate the close relationship of these actual hydrograph patterns to the scores hydrograph for KA - PC1 (Figure 15a). A continuous long term drop accompanied by increasing seasonal fluctuations is detected in the average water level in the wells of this group.



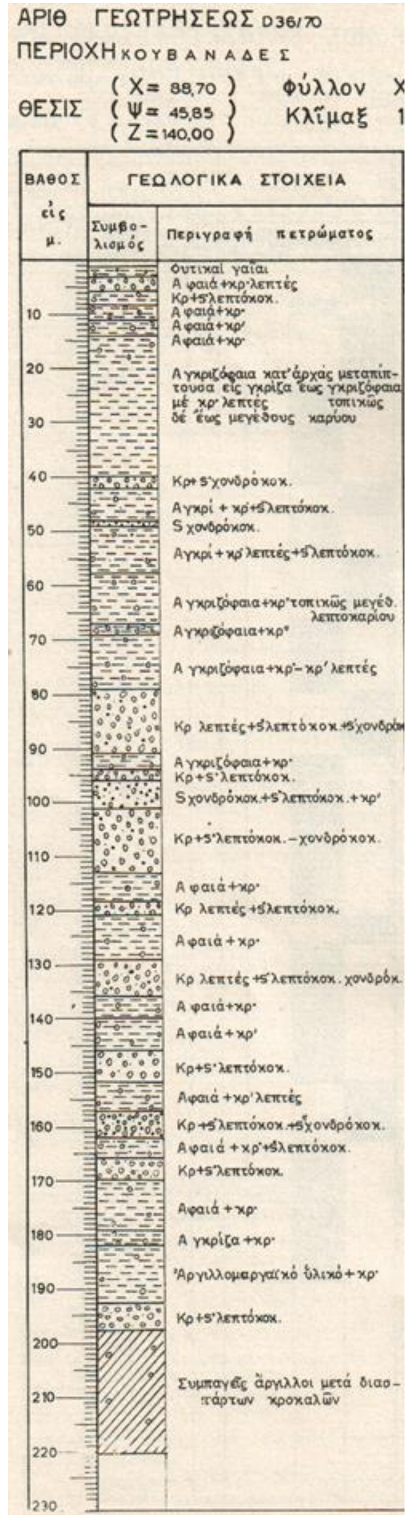


Figure 16: Geological logs of D30 and D36 monitoring wells in group 1 of Karditsa. Clay, gravels and sand are encountered.

At the other extreme, wells D37 and PZ32 that have high loadings on KA - PC2 and low loadings on KA – PC1 and KA - PC3 on the upper left side of the diagram (Figure 22) are designated as group 2. A hydrograph of actual water levels in one of these wells, i.e. PZ32 (Figure 15b) indicates the close relationship of this hydrograph pattern to the scores hydrograph for KA - PC2 (Figure 15b). In contrast to the first group, these hydrographs show a more or less stabilized long term trend, while their seasonal behavior is characterized by strong biennial patterns (Figure 17).

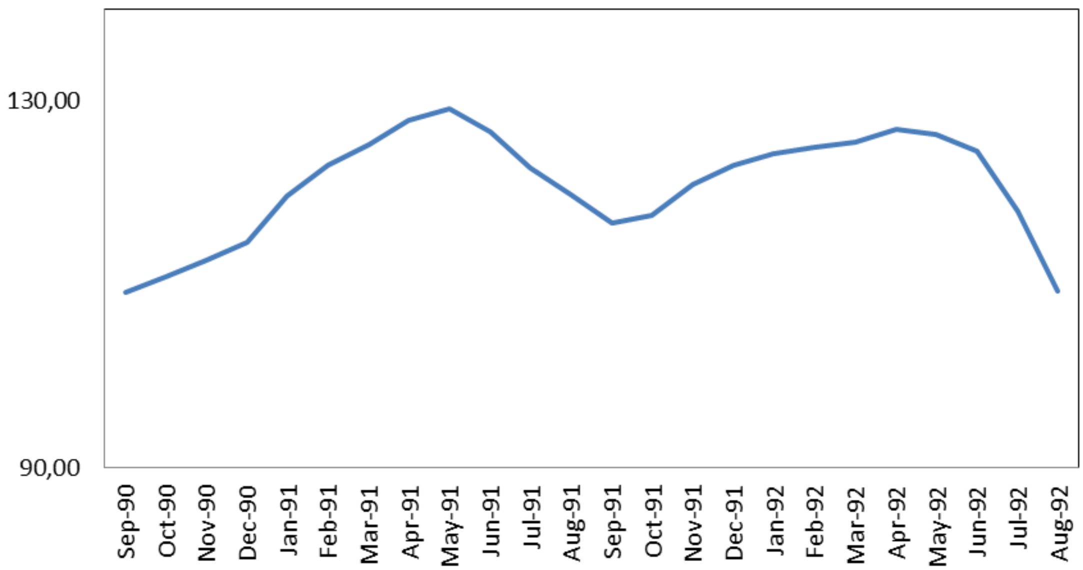


Figure 17: Biennial pattern of monitoring well PZ32

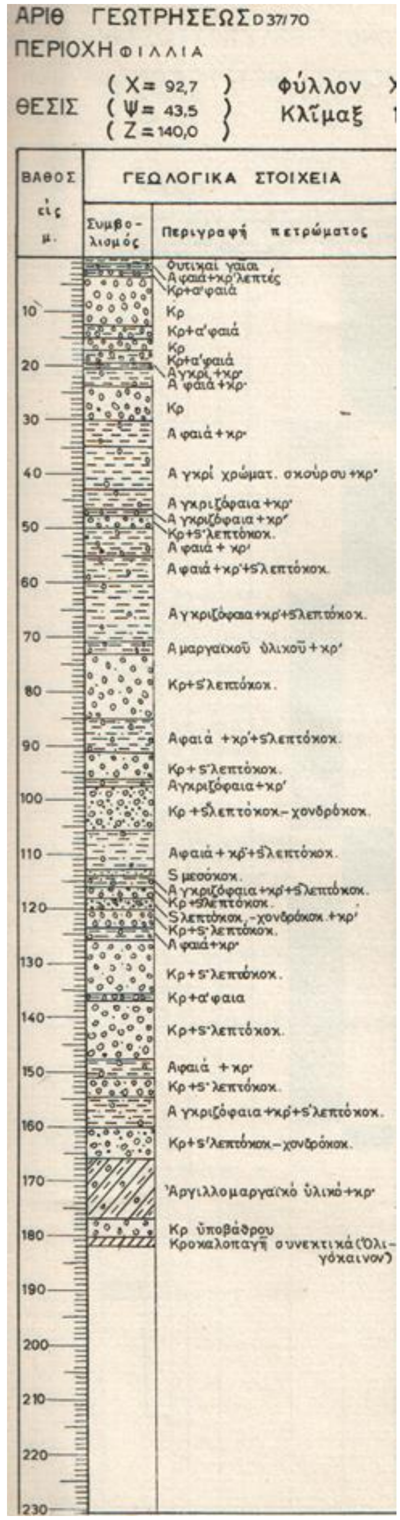
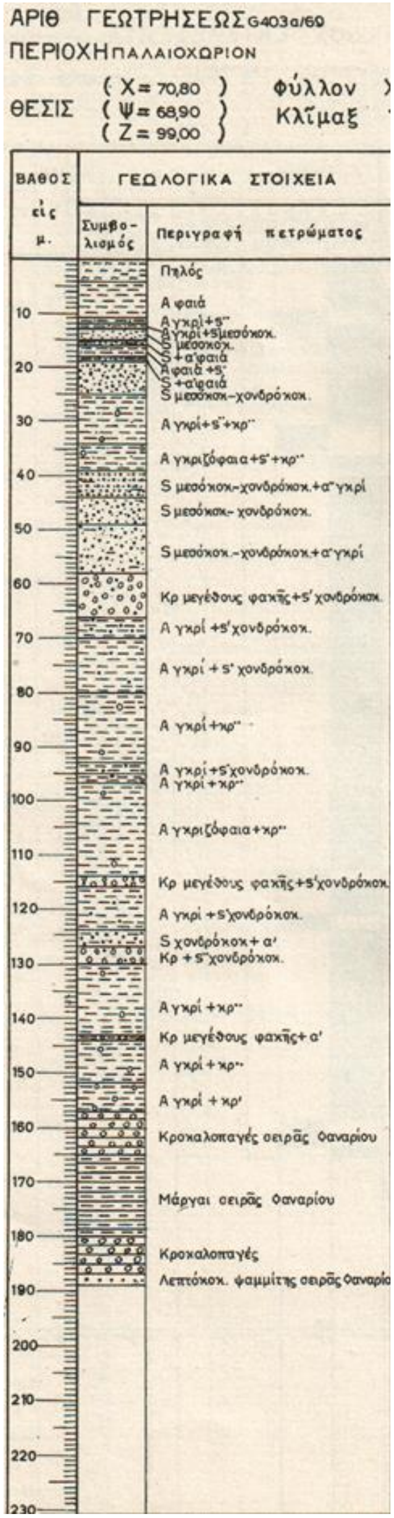


Figure 18: Geological log of D37 monitoring well in group 2 of Karditsa. Most clay and gravels are encountered.

A third group consists of wells G403, G407, G408, G503, G504, G505, G506, PZ19a and SR11 having relatively high loadings on KA - PC3 and moderately high loadings on KA - PC1 and KA - PC2. Hydrographs of actual water levels for one of these wells, i.e. PZ19a (Figure 15c) present some of the characteristics of the scores hydrographs for KA - PC3 (Figure 15c). In fact, they show a similar type of seasonal response to the second group of Karditsa wells, with the exception of two sudden drops in water levels recorded in 1978 and 1984.



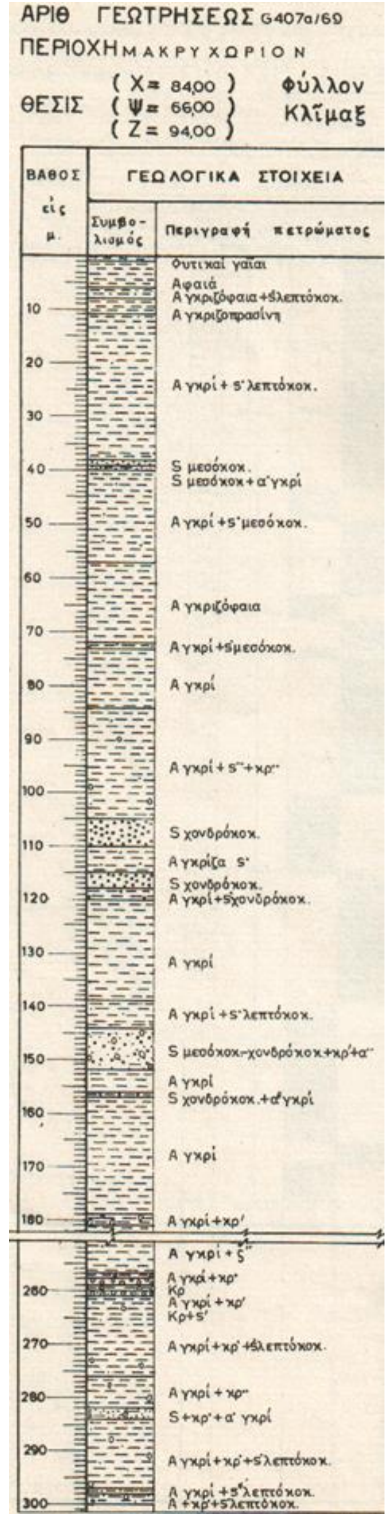
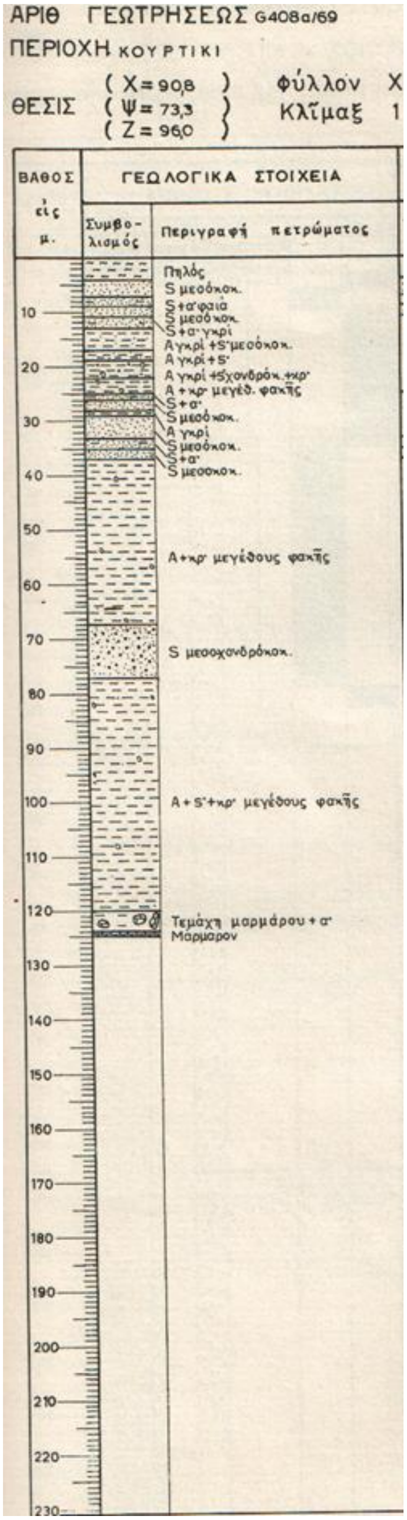


Figure 19: Geological logs of G403 and G407 monitoring wells in group 3 of Karditsa. Most clay is encountered.



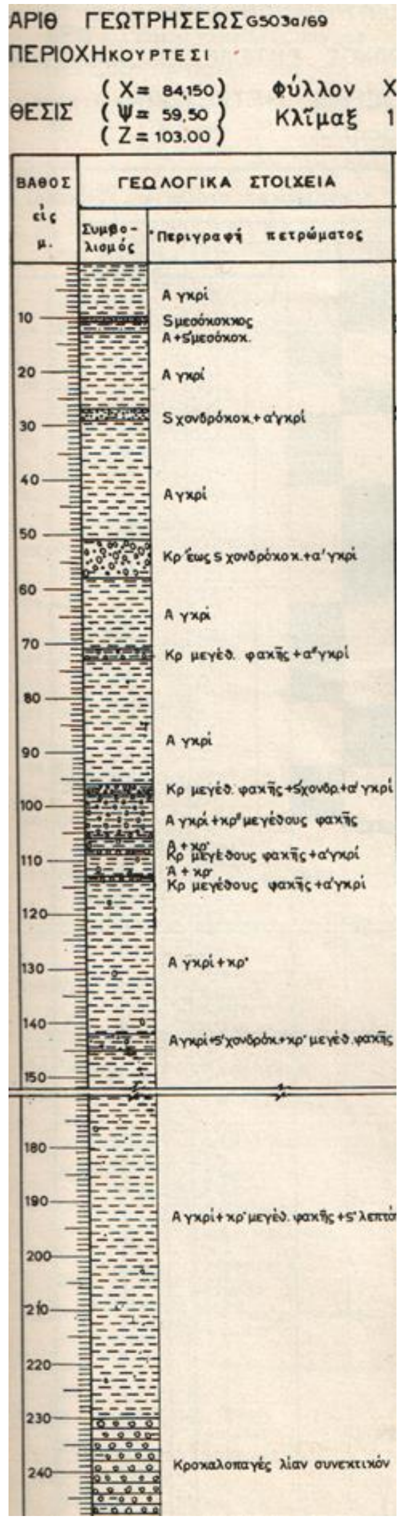
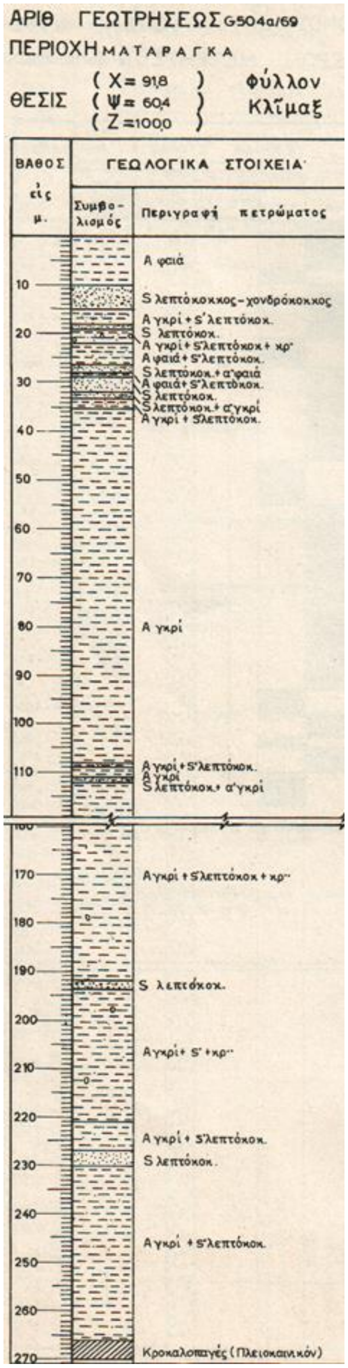


Figure 20: Geological logs of G408 and G503 monitoring wells in group 3 of Karditsa. Most clay is encountered.



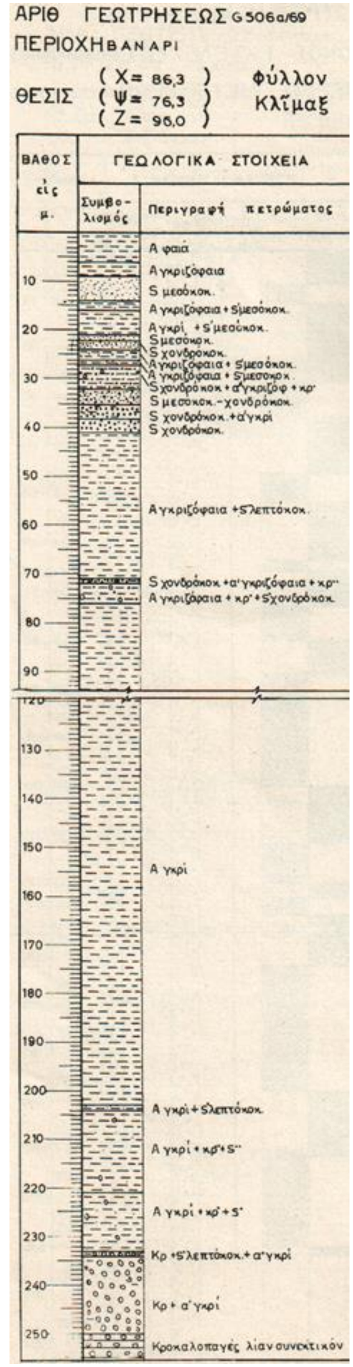


Figure 21: Geological logs of G504 and G506 monitoring wells in group 3 of Karditsa. Most clay is encountered.

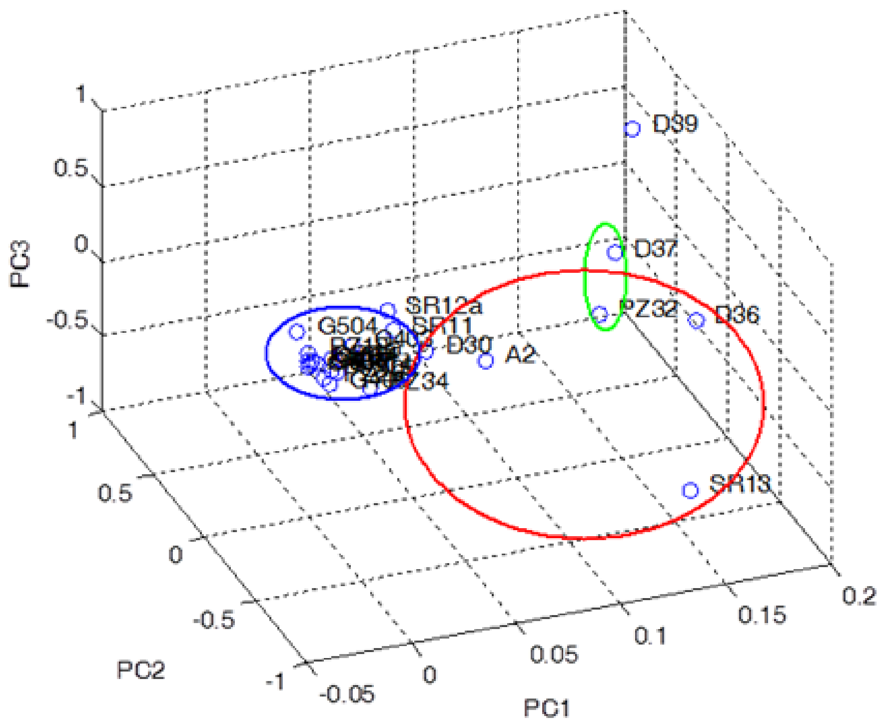


Figure 22: Plot of component loadings for each well in Karditsa related to the three principal components.

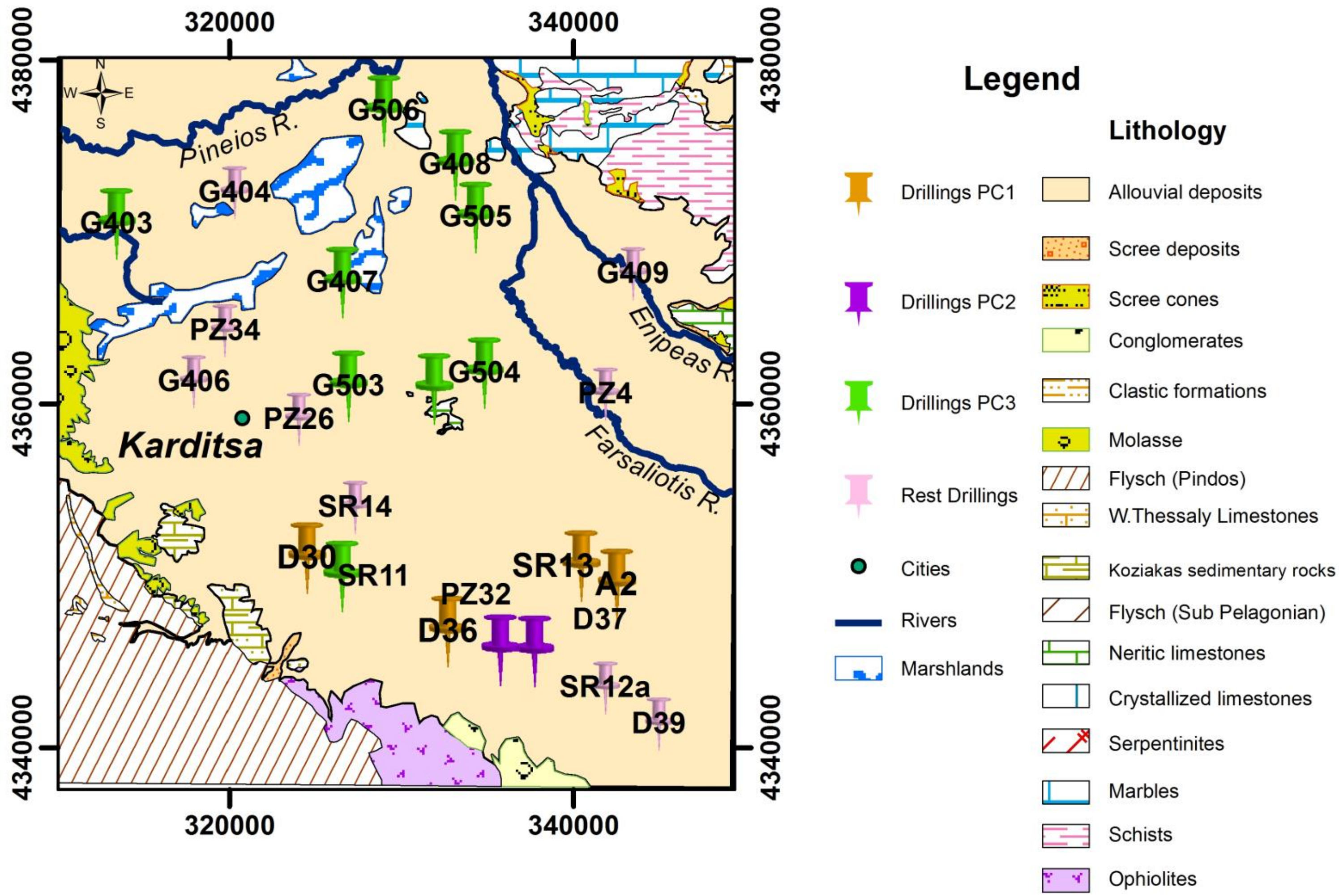


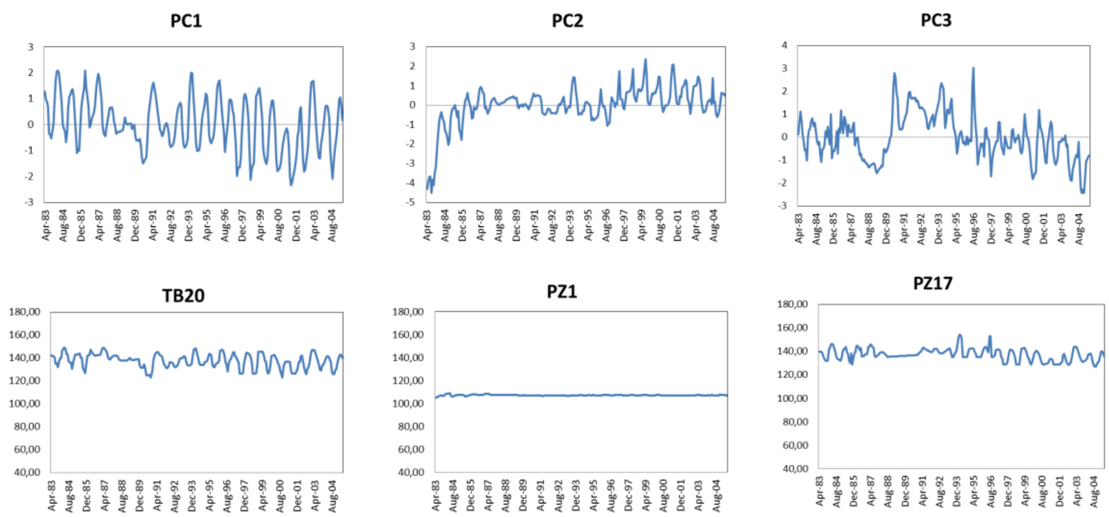
Figure 23: Configuration of the geological formation on the land surface and areal distribution of well groups in Karditsa area.

A map of the location of the well groups identified in Figure 23 and the relevant rock formations prevailing in these areas can be used to elucidate the causes of the actual hydrograph patterns. For example, as shown in Figure 23, the water table is located in alluvial formations in almost all wells examined in the Karditsa area. Additionally, borehole loggings indicate clay, gravels and sand in group 1 (Figure 16), mostly clay and gravels in group 2 (Figure 18), while in group 3 mostly clay is encountered (Figure 19, Figure 20, Figure 21) (Hydroerevna 1972; Kallergis et al. 1973). On the other hand, all the wells classified in group 1 and 2 are found upgradient of Karditsa and near the surface recharge zone, as shown in Figure 3. Due to the above conditions in this area, it is justified that in the first and second group of wells the continuously increasing rate of groundwater exploitation results to a drop in the average water level and to an increase in seasonal fluctuations. On the contrary, the biennial patterns in groups 2 and 3 cannot be attributed strictly to the prevailing geological conditions, but it may have to be related with a result of manmade activities. Finally, the response of the group 3 wells to the 1978 drought and the 1984 overexploitation periods (Marinos et al. 1995) can be explained by the low volume aquifer due to the increase clay content of the alluvial formations in this area.

6.3 Trikala Area

For the Trikala area, the data of thirty (30) wells monitored for 23 years were examined. In this area the first principal component (Trikala - Principal Component 1, TR - PC1) accounted for 65% of the variance in the water level data, the second principal component (TR - PC2) for 8% of the variance and the third principal component (TR - PC3) accounted for 6% of the variance in the water level data (Table 1). As previously noted the data set of the Trikala area presents the higher number of monitoring wells and the lower percentage variance of available data versus the three principal components.

Scores hydrographs for TR - PC1, TR - PC2 and TR - PC3 are shown in Figure 24.

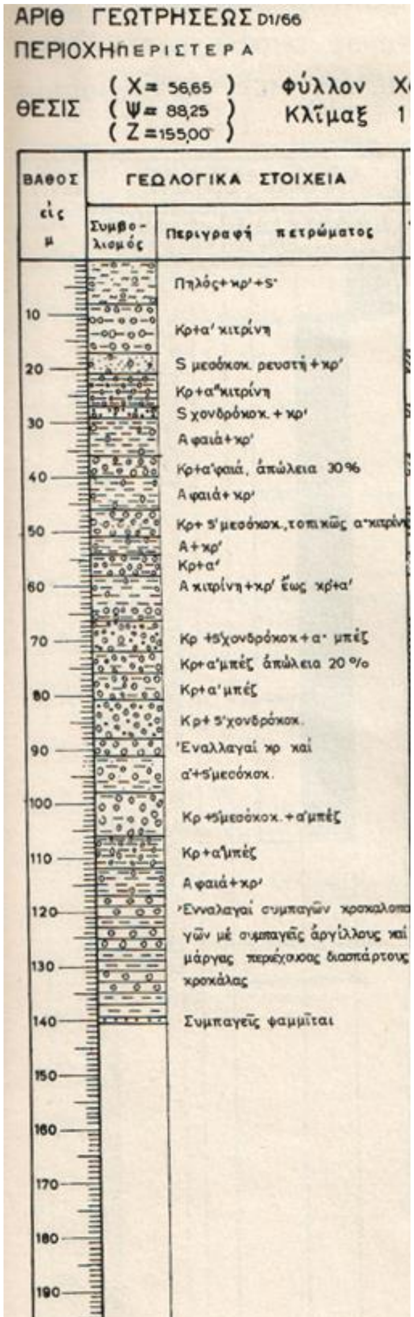


(a) (b) (c)

Figure 24: Component scores plot and hydrographs of representative monitoring wells for the three principal components in Trikala area.

A plot of the component loadings for each well as they relate to TR – PC1 versus TR - PC2 and TR - PC3 (Figure 30) indicates that again in the Trikala area the wells fall into three groups regarding the variations observed in water level data.

Wells D1, D22, D25, D27, 174, PZ54, PZ57, SR92 and TB20 that have high loadings on TR – PC1 and low loadings on TR - PC2 and TR - PC3 on the lower right side of the diagram are designated as group 1. Hydrographs of actual water levels for one of these wells, i.e. TB20 (Figure 24a) indicate the close relationship of these actual hydrograph patterns to the scores hydrograph for TR - PC1 (Figure 24a). A continuous long term drop is detected in the average water level in the wells of this group.



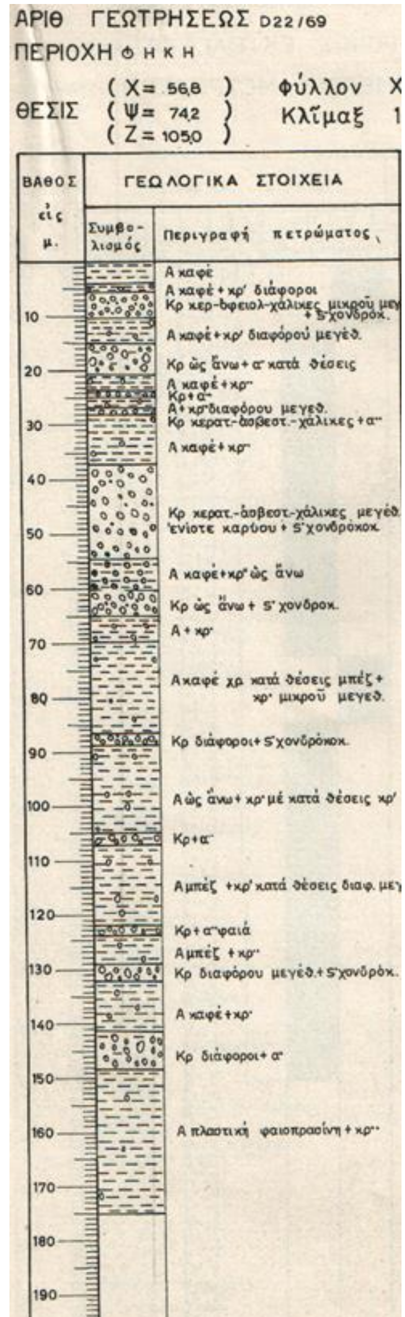
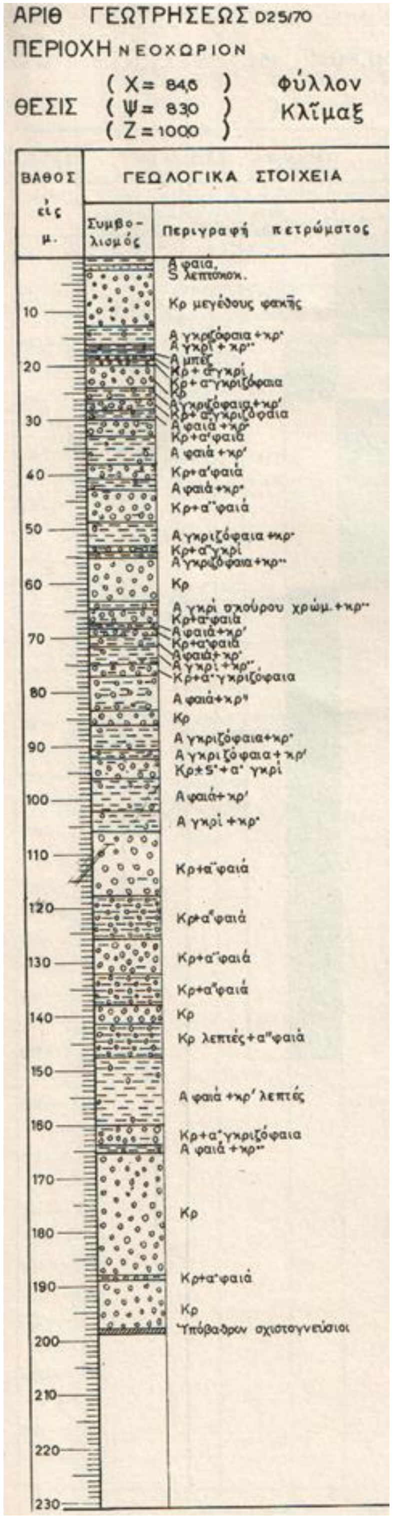


Figure 25: Geological logs of D1 and D22 monitoring wells in group 1 of Trikala. Most clay and gravels are encountered.



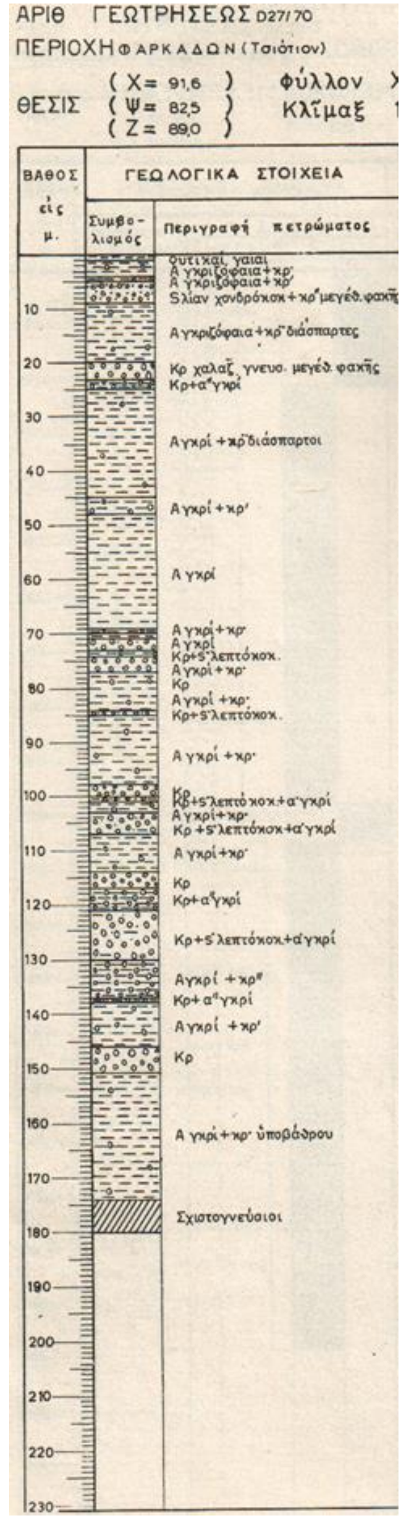


Figure 26: Geological logs of D25 and D27 monitoring wells in group 1 of Trikala. Mostly clay and gravels are encountered

At the other end, wells 25, 112T, 3a, 84T, D10, D16, D21, D5, G402, G405, G501, P2, PZ1, PZ28, PZ3, PZ30, PZ55 and PZ70 that present high loadings on TR - PC2 and low loadings on TR – PC1 and TR - PC3 on the upper left side of the diagram (Figure 31) are designated as group 2. A hydrograph of actual water levels in one of these wells, PZ1 (Figure 24b) indicates a very weak, if any, relationship of this hydrograph pattern to the scores hydrograph for TR - PC2 (Figure 24b). In contrast to the first group, they show a more or less initially increasing and then stabilized long term trend.

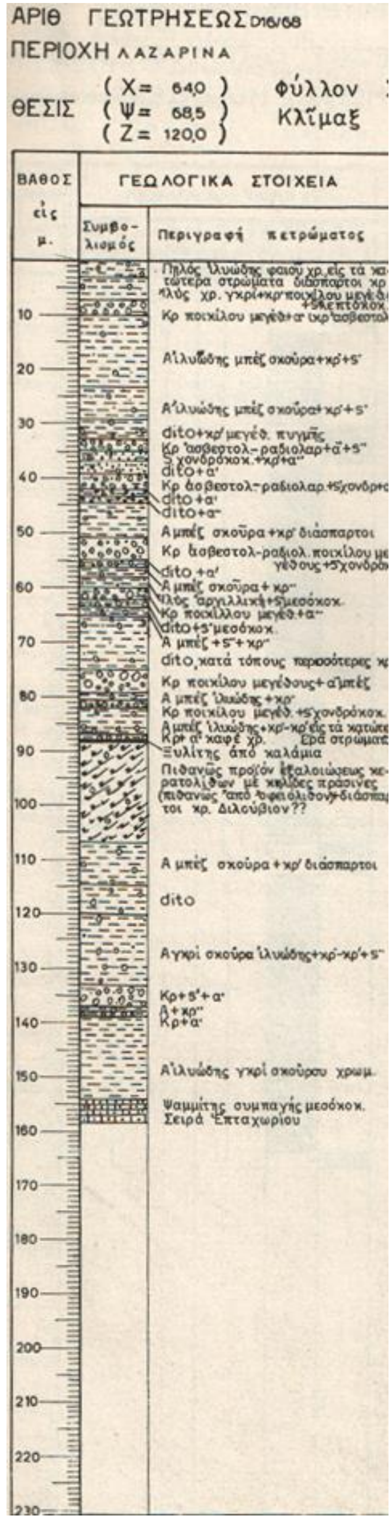


Figure 27: Geological log of monitoring well D16 in group 2 of Trikala. Mostly clay and sand are encountered.

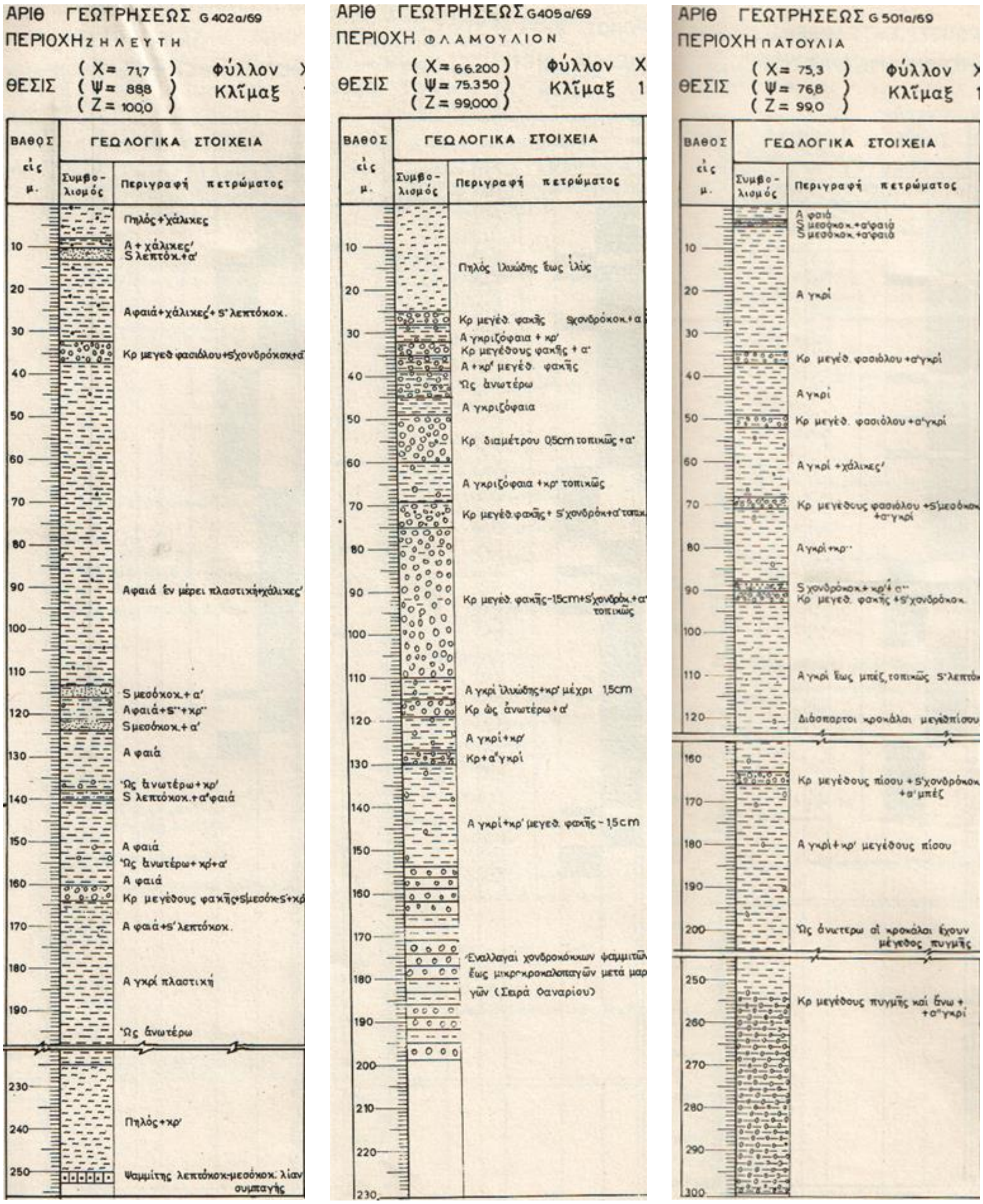


Figure 28: Geological logs of monitoring wells G402, G405 and G501 in group 2 of Trikala. Mostly clay and sand are encountered.

A third group consists of wells PZ17, PZ18, D2 having relatively high loadings on TR - PC3 and moderately high loadings on TR - PC1 and TR - PC2. Hydrographs of actual water levels for one of these wells, i.e. PZ17 (Figure 24c) indicate some characteristics of the scores hydrographs for TR - PC3 (Figure 24c). In fact, they show some type of seasonal response characterized by cycles which repeat every 3-4 years.

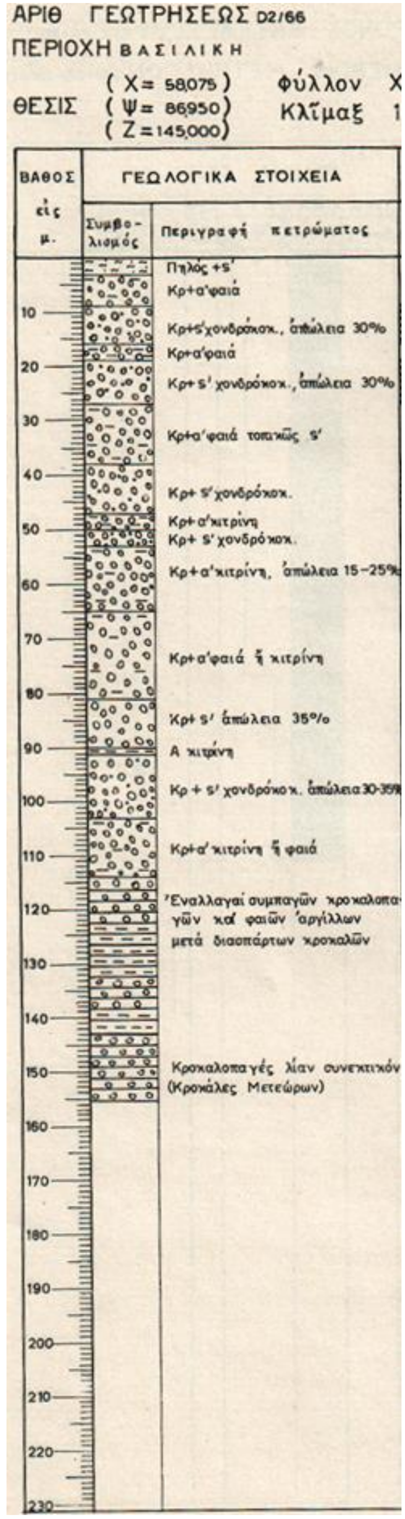


Figure 29: Geological log of monitoring well D2 in group 3 of Trikala. Mostly clay and gravels are encountered.

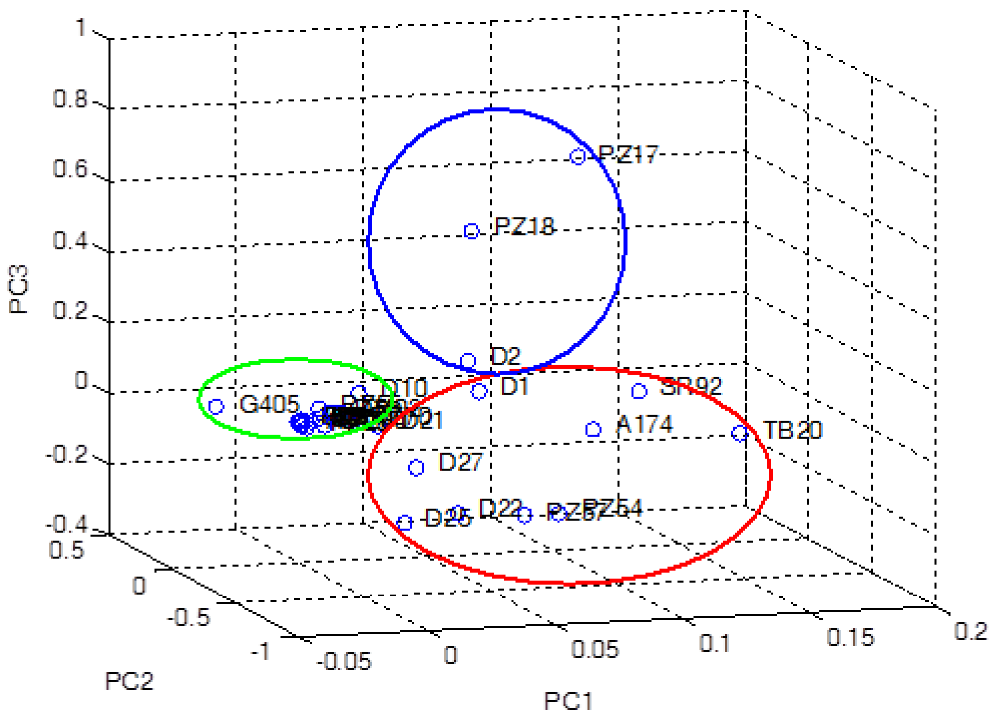


Figure 30: Plot of component loadings for each well in Trikala related to the three principal components.

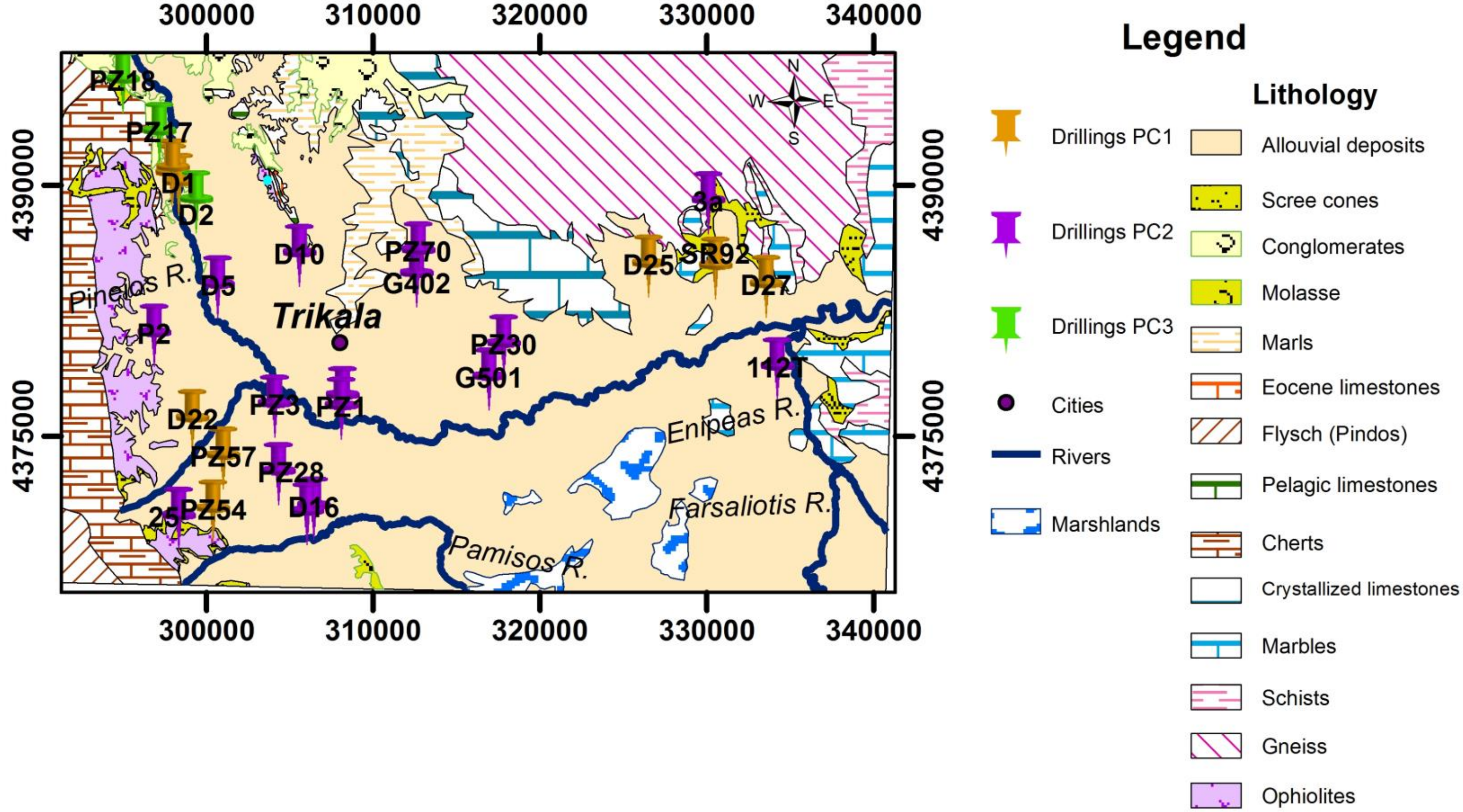


Figure 31: Configuration of the geological formation on the land surface and areal distribution of well groups in Trikala area.

A map of the areal distribution of the well groups identified in Figure 31 and the respective geological formation recorded on the surface of these areas can be used to develop insight into the causes of the actual hydrograph patterns. For example, as shown in this Figure, the water table is located in alluvial deposits at almost all wells of group 2, while groups 1 and 3 are located near background formations. Additionally, borehole loggings indicate mostly clay and gravels in groups 1 (Figure 25, Figure 26) and 3 (Figure 29), while in group 2 more clay and sand are encountered (Figure 27, Figure 28) (Hydroerevna 1972, Kallergis et al. 1973). On the other hand, all wells classified in groups 1 and 3 are found upgradient of Trikala watershed, as shown in Figure 3. Because of the above conditions in this area, it seems reasonable that in the second group of wells, the average water level is rather stabilized. On the contrary, the perennial patterns in group 3 cannot be attributed strictly to the prevailing geological conditions, but it may have to be related with a result of anthropogenic influence.

7. Conclusions

Based on the findings of the present study it is clearly concluded that in order to assess the overall water balance of the West Thessaly basin, an area where intense water abstraction has resulted in the lowering of the water table and extensive surface land subsidence a systematic monitoring from the authorities is required.

To establish a well-documented water balance in this area, including surface and ground waters, the following information is needed: reliable meteorological data, monitoring of the flows of Pineios river and its affluents and also a continuous monitoring of ground water level at appropriate locations. All the above data will result in a reliable, well documented evaluation of West Thessaly's water potential, both surface and underground. These data can then be compared with the irrigation water volumes abstracted from surface and ground waters and used in the agriculture activities as well as potable water abstractions, so as to develop an overall water balance of the area and ensure that appropriate measures, both preventive and mitigation, are applied for the sustainable management of the available water resources in this area

From all the above types of data, this work focuses on the optimization of groundwater monitoring in three sub-basins of the West Thessaly basin, namely the Farsala, Karditsa and Trikala sub-basins extended to areas of 250, 1200, and 700 km^2 respectively.

The application of the Principal Component Analysis on the hydrographs from 62 monitoring wells recorded in the period 1974-2014, revealed the existence of distinct temporal patterns in the available water level data. This allows the classification of wells into groups of similar behavior. This behavior was further analyzed based on the geological and hydrogeological conditions encountered in the above areas, taking also into account th borehole logs of the examined monitoring wells. Then, it is possible to locate certain target wells one from each of the above well groups that can be selectively monitored in the long -term, allowing the sustainable monitoring and the collection of reliable ground level data.

At the Farsala area where 8 wells were analyzed, according to the statistical analysis along with the principal components analysis of the monitoring wells hydrographs, 3 monitoring wells, one for each different type, were selected as representative. Namely, LB70 as a typical example of PC1, 540B of PC2 and SR4 for PC3. It is noted that in PCI wells, the monitored water table is located in alluvial formations, where lower hydraulic conductivity results to slower recharge rates. Due to the above conditions, water table fluctuations reflect more seasonal and longer-term recharge conditions. In contrast, groups PC2 and PC3 are found upgradient of

Farsala water table and near the surface recharge zone which is developed within limestones. As a result, in these wells water table fluctuations are abrupt and they promptly respond to aquifer recharge. Groundwater recharge is seen to generally balance or in periods exceed water abstraction for potable water and irrigation as suggested by the long term trend of water level variation.

At Karditsa, where the hydrographs of 24 wells were examined, the monitoring wells D36, PZ32, PZ19a were selected for better representation of each group to match each factor. It is noted that in almost all wells examined in the Karditsa area the water table is found in alluvial formations. Additionally, borehole loggings indicate clay, gravels and sand in group 1, mostly clay and gravels in group 2, while in group 3 mostly clay is encountered. Based on the hydrogeological data it is justified that in the first and second group of wells the continuously increasing rate of groundwater exploitation results to a drop in the average water level and to an increase in seasonal fluctuations. On the contrary, the biennial patterns recorded in the hydrographs in groups 2 and 3 cannot be attributed strictly to the prevailing geological conditions, but it may be related with manmade activities. Finally, the response of the group 3 wells to the 1978 drought and the 1984 overexploitation periods can be attributed to the low volume of the aquifer due to the increase clay content of the alluvial formations in this area.

Finally, at Trikala, TB20, PZ1, PZ17 are the monitoring wells in this area that conform with PC1, PC2 and PC3 respectively. Based on geological data, the water table is located in alluvial deposits at almost all wells of group 2, while groups 1 and 3 are located near background formations. Additionally, borehole loggings indicate mostly clay and gravels in groups 1 and 3, while in group 2 more clay and sand are encountered leading to a stable average water level. On the contrary, the perennial patterns in group 3 cannot be attributed strictly to the prevailing geological conditions, but it may have to be related with a result of manmade activities.

To sum up, as a result of this study, it is concluded that the application of the PCA method, combined with the hydrogeological evaluation of the hydrographs recorded, allows the significant reduction in the number of wells to be monitored in the Thessaly area without jeopardizing the accuracy of the data input. More specifically, as concluded in this study, groundwater level can be continuously monitored in only 9 instead of 62 monitoring wells in the three sub-basins of the West Thessaly area, so as to allow the competent water authorities to compile the necessary, reliable data for the sustainable water management in this region.

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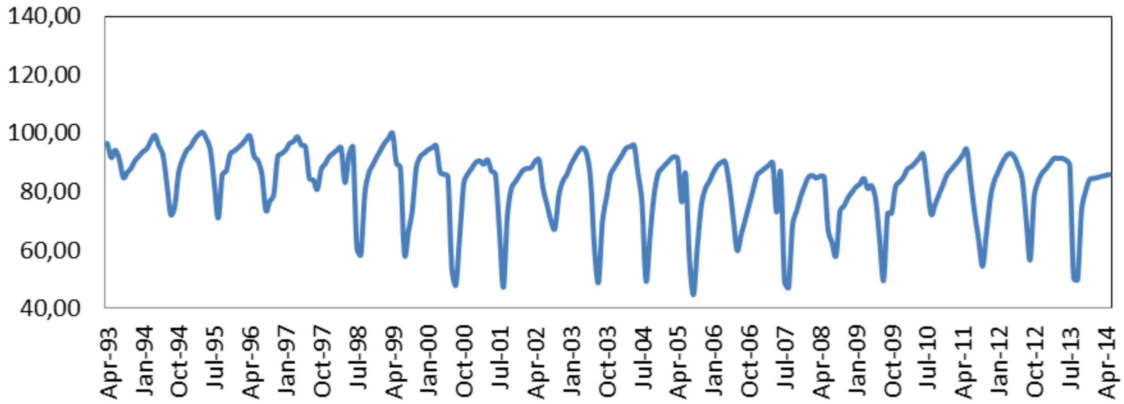
Appendix

FARSALA_PC1



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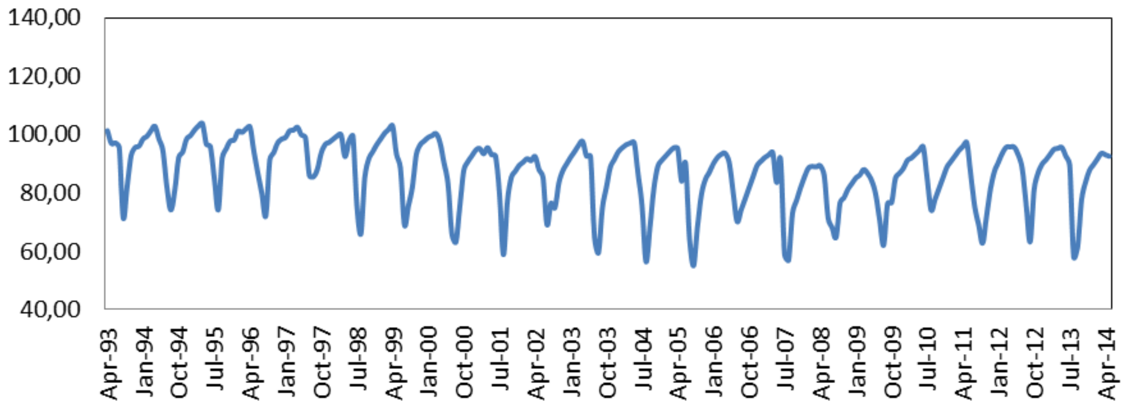

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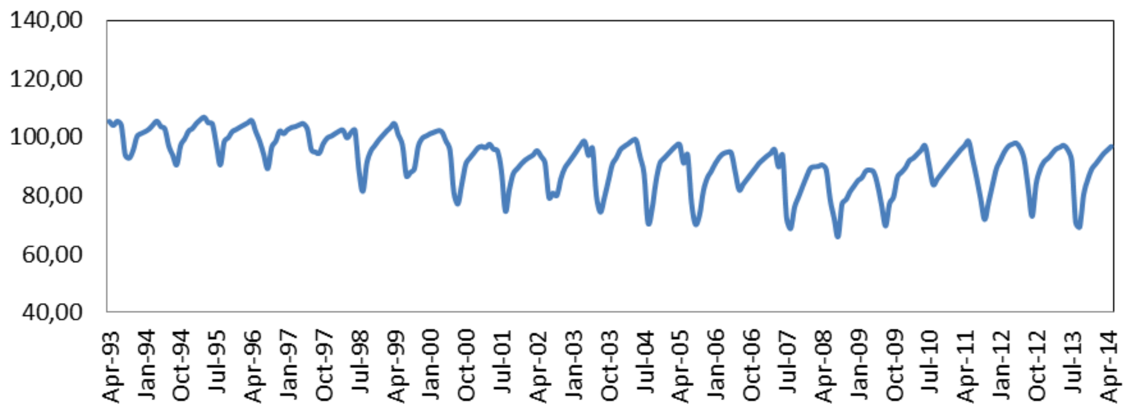

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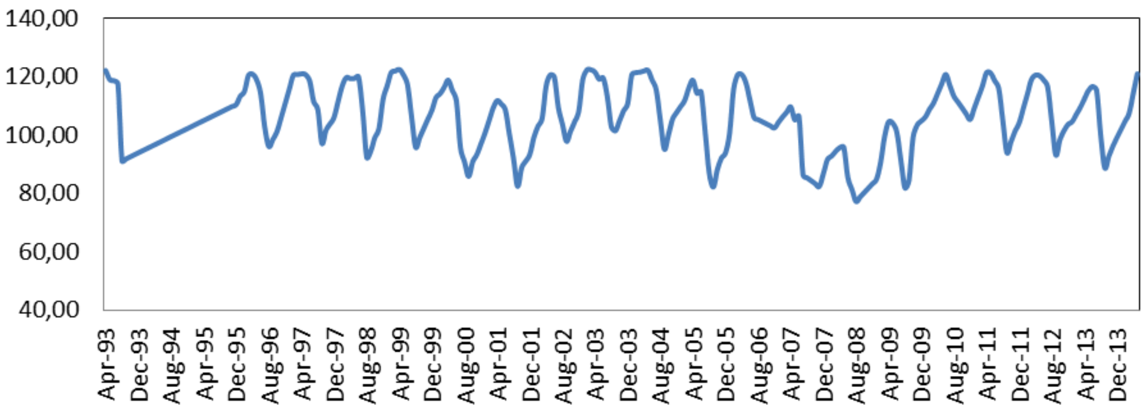

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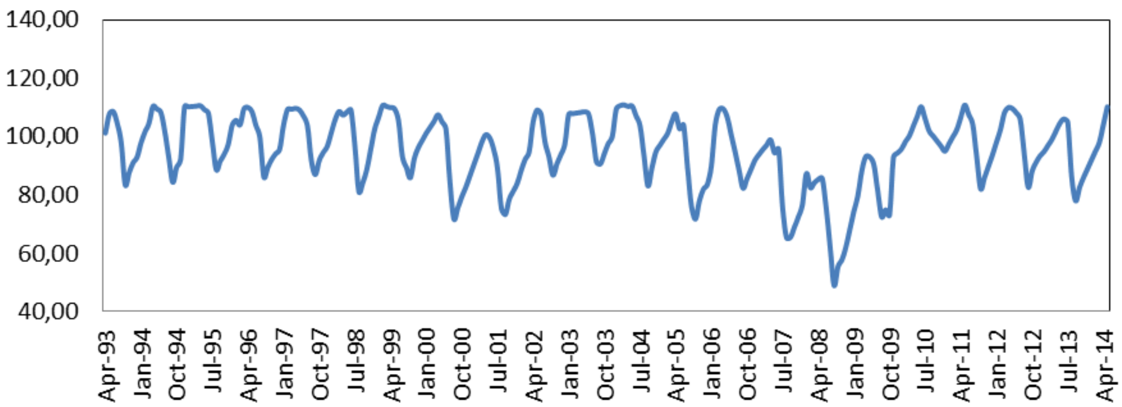

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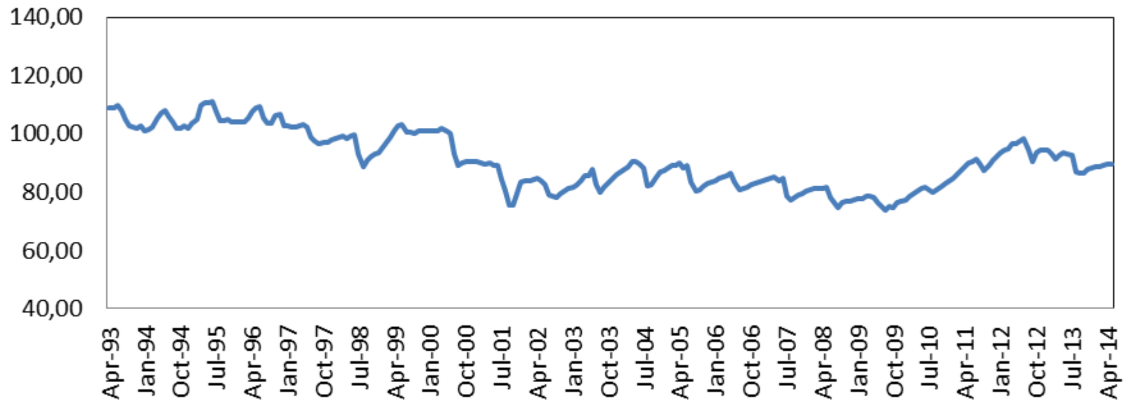

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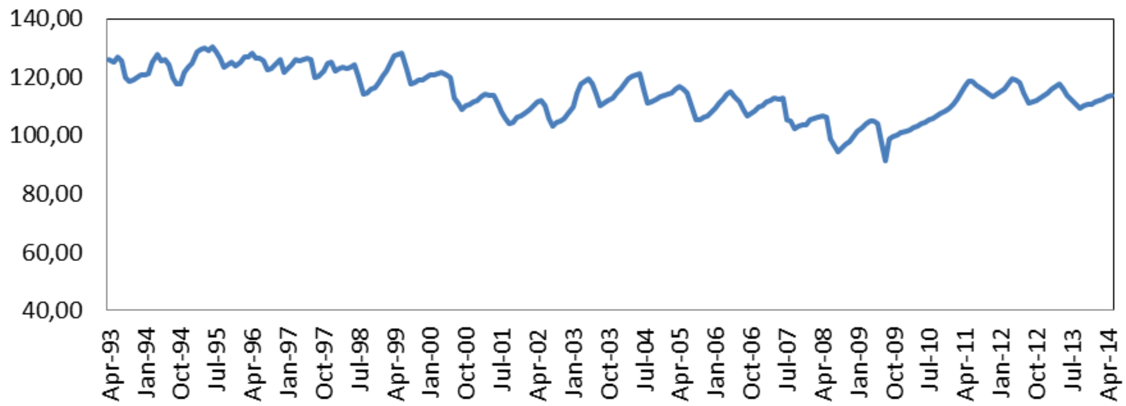

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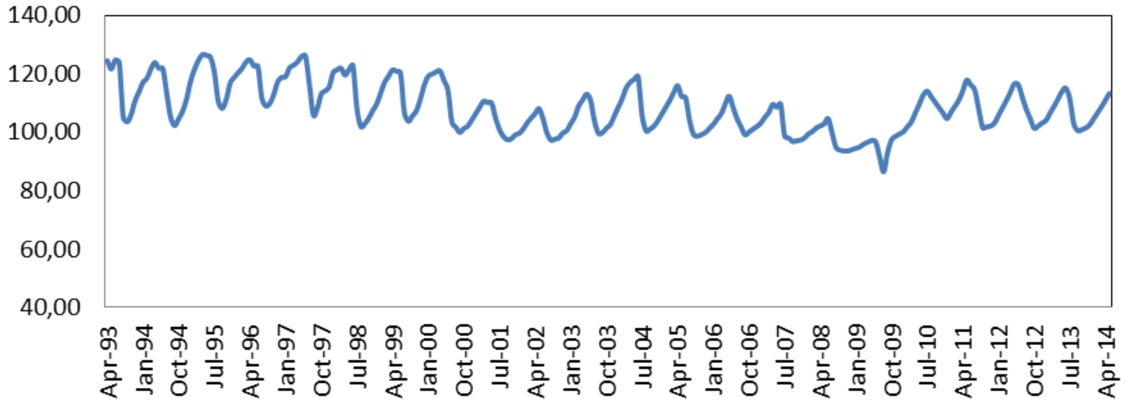
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SR4

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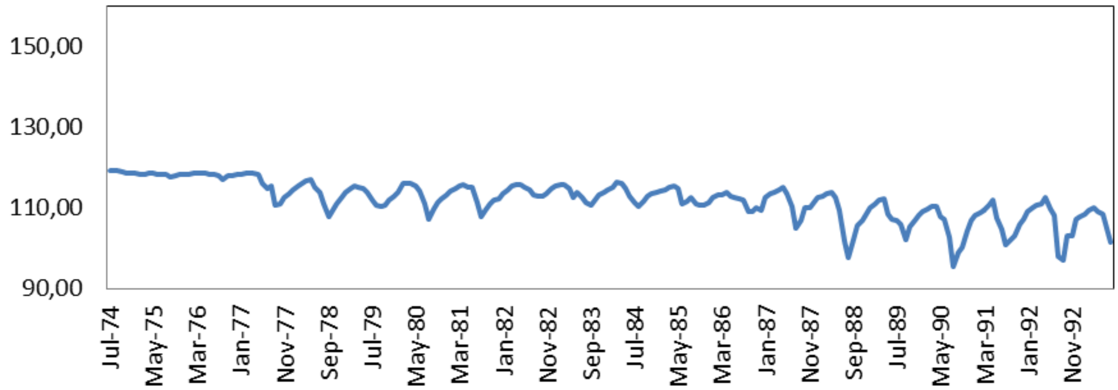

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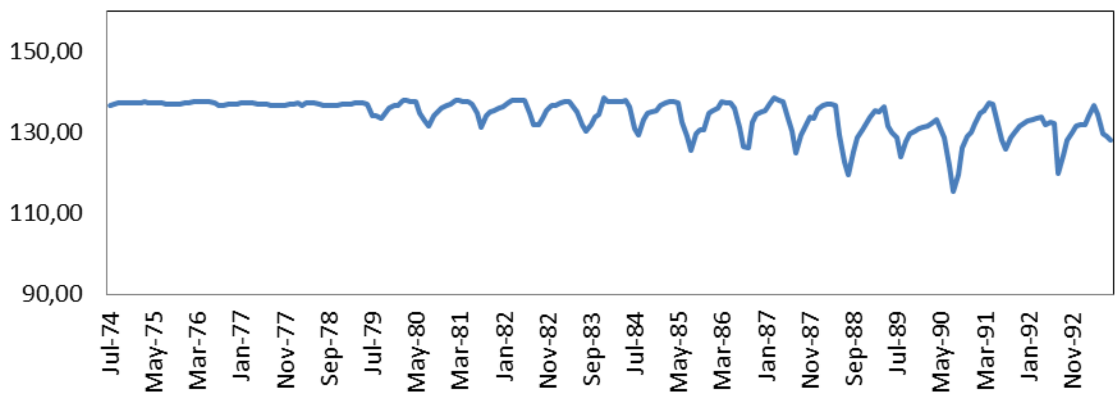

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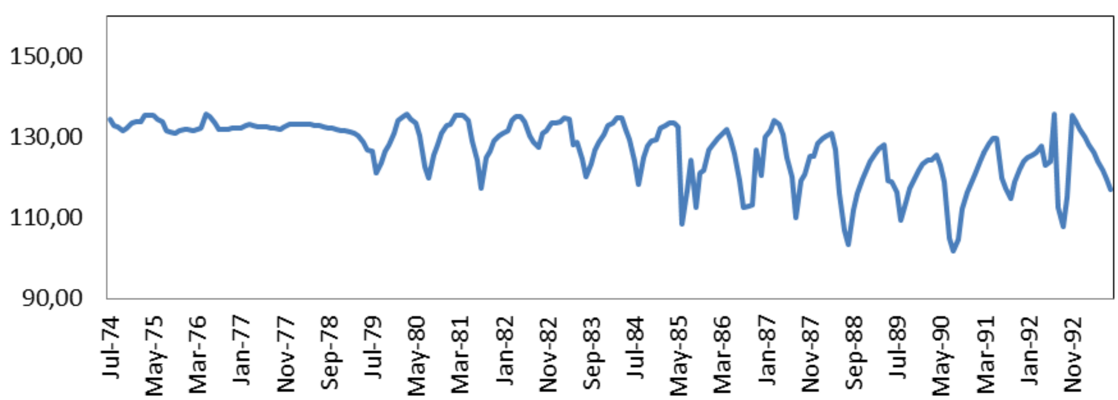

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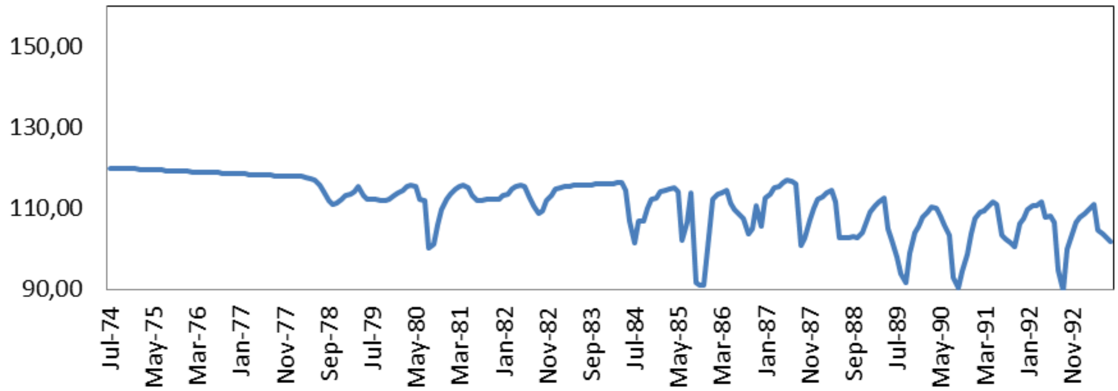
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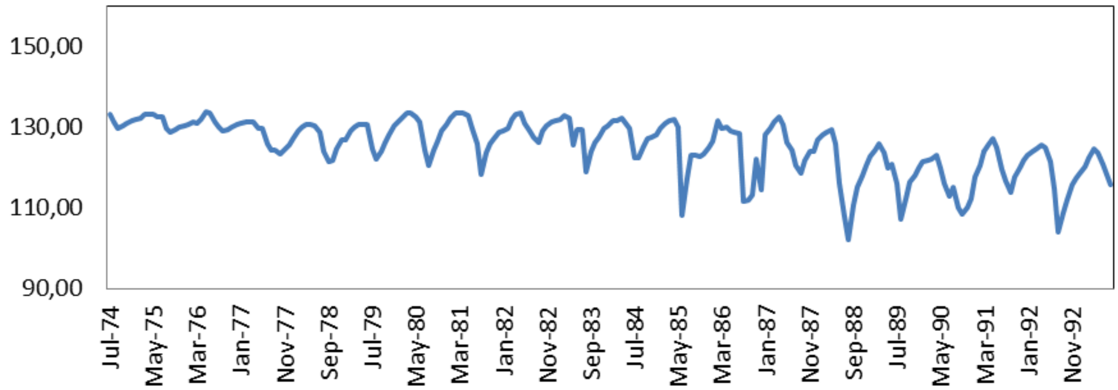

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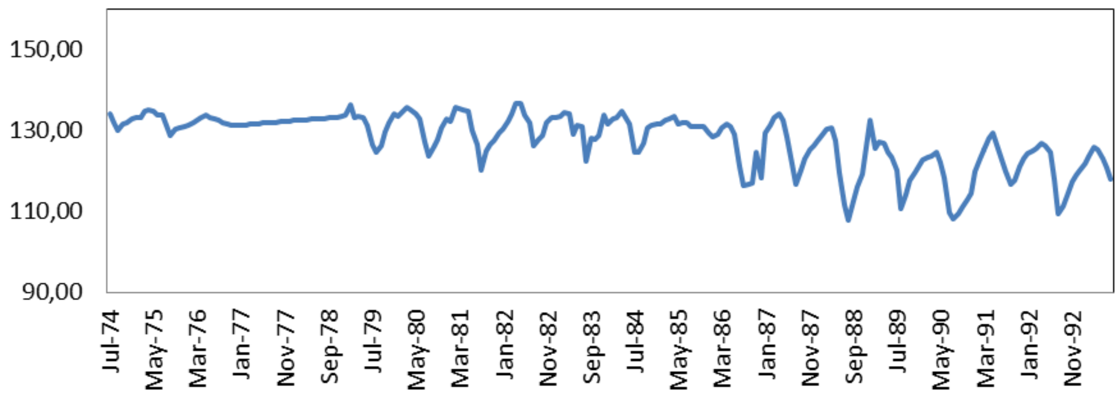

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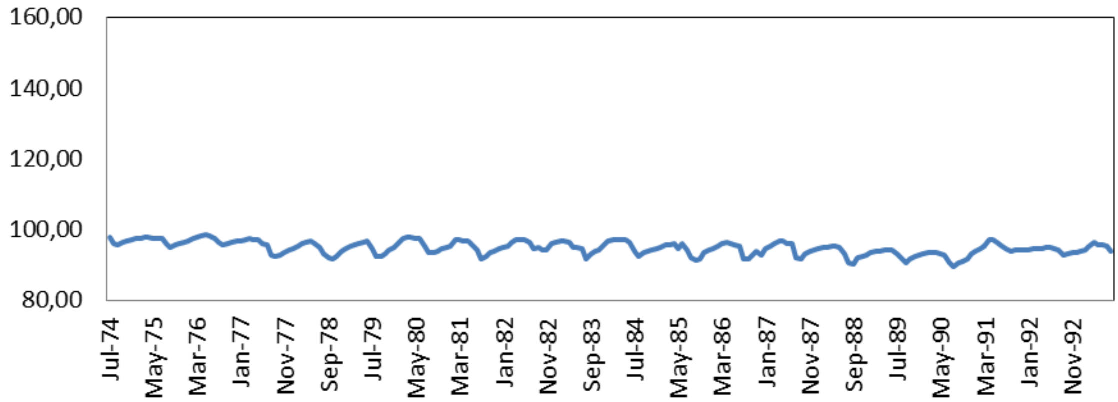

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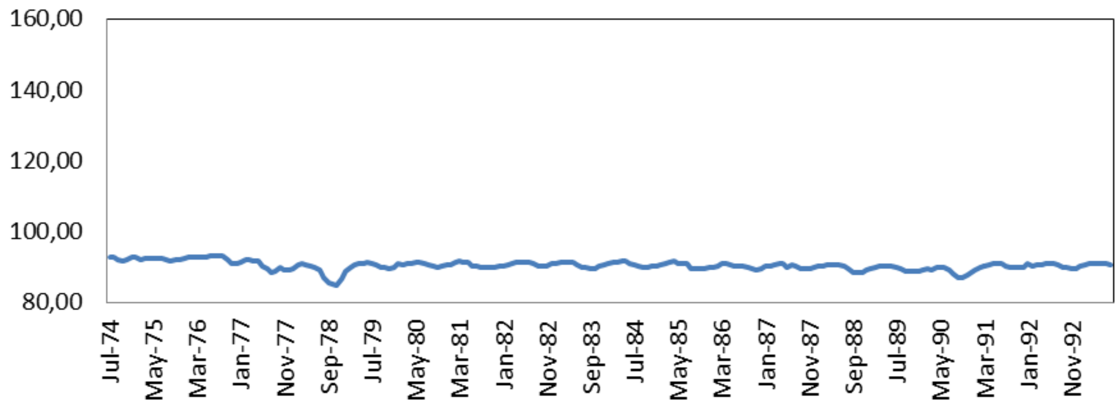

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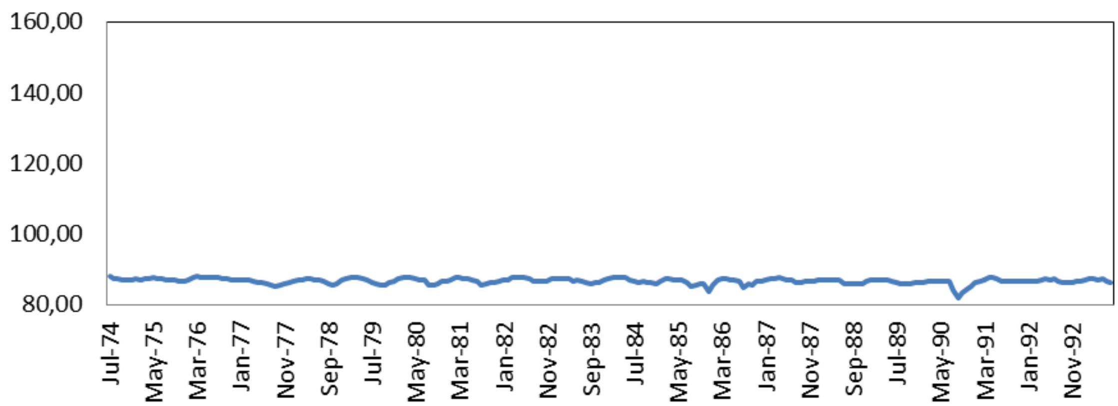

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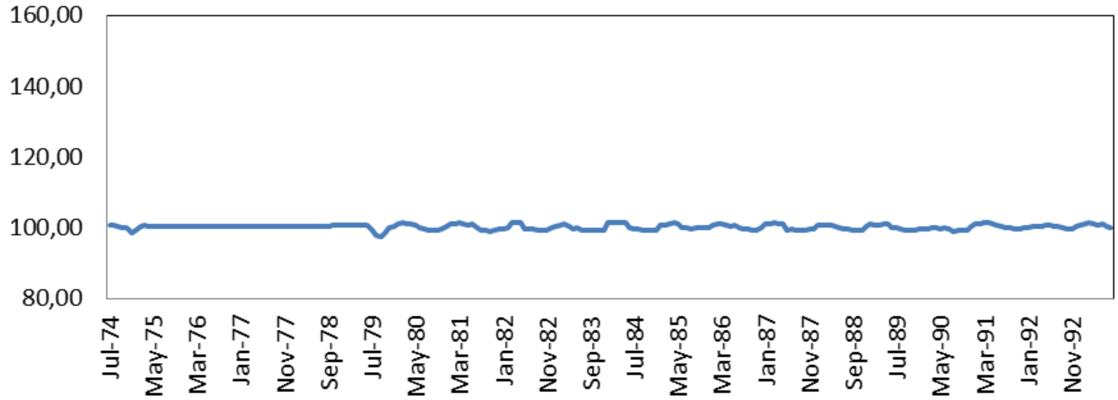

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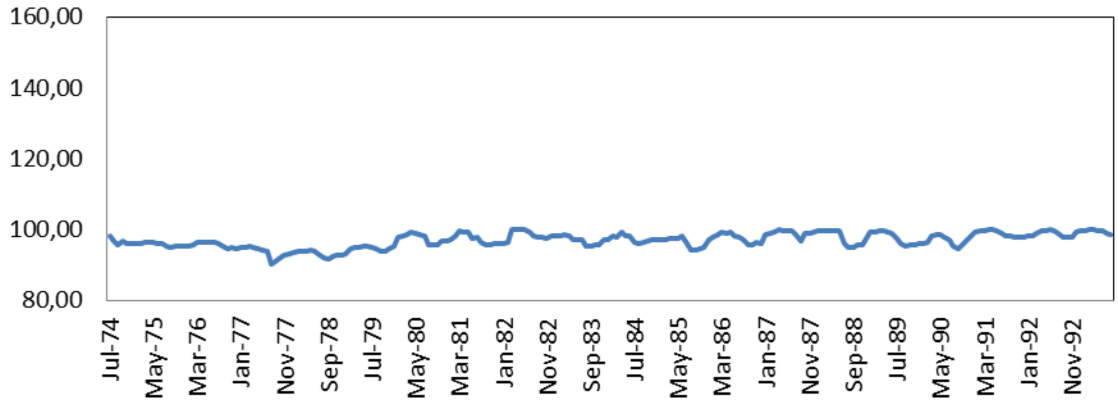

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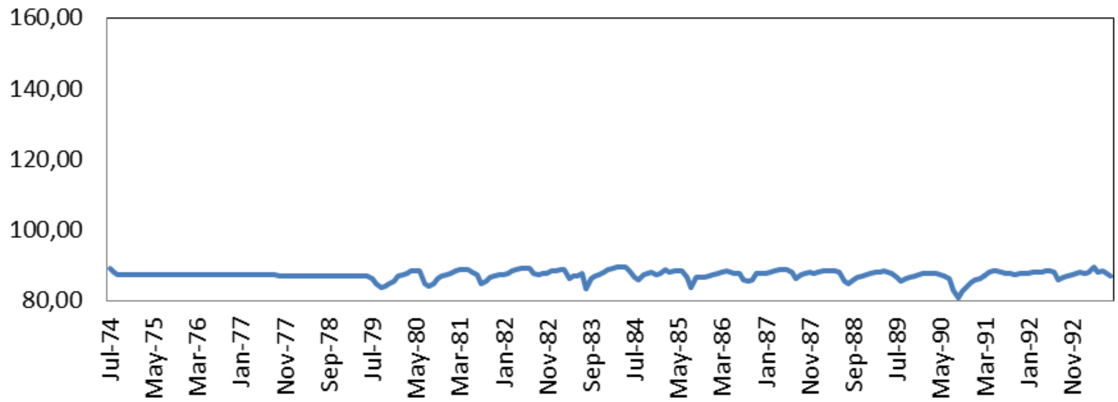

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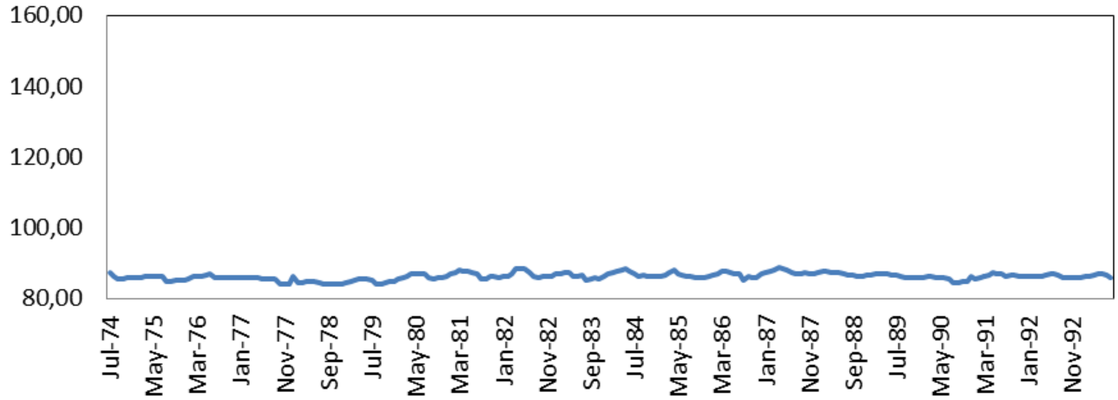

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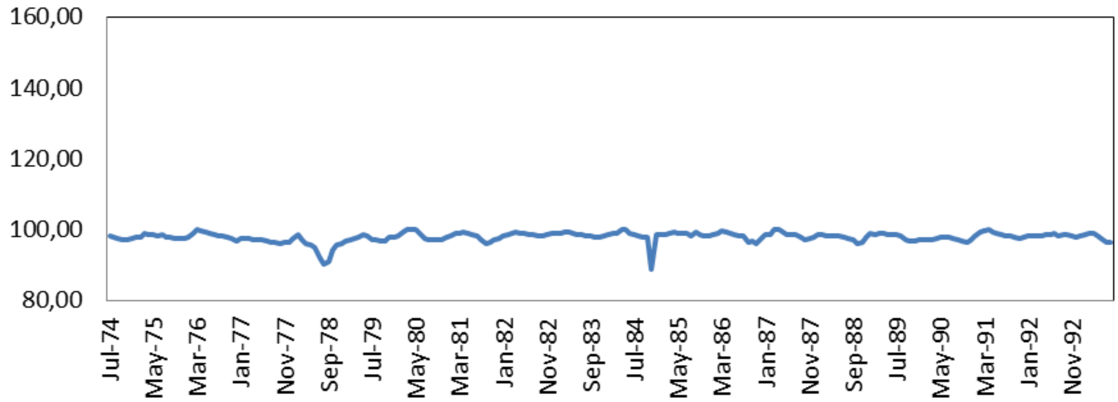

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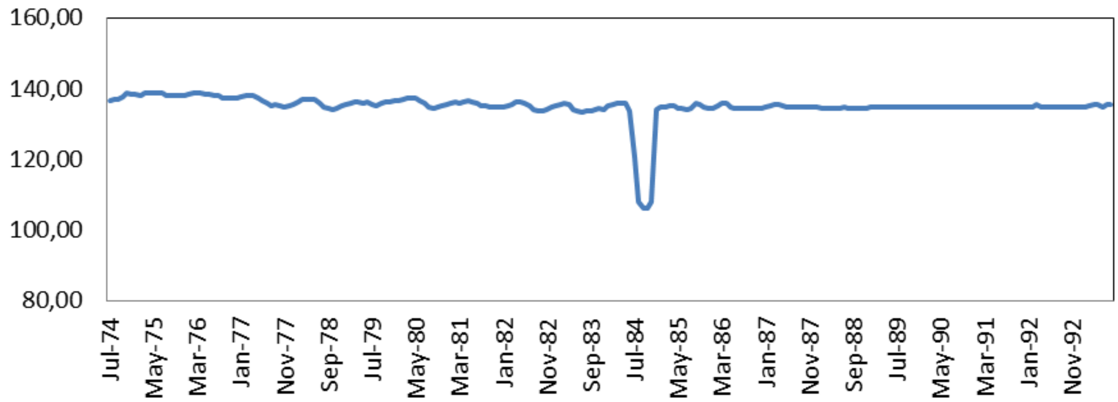

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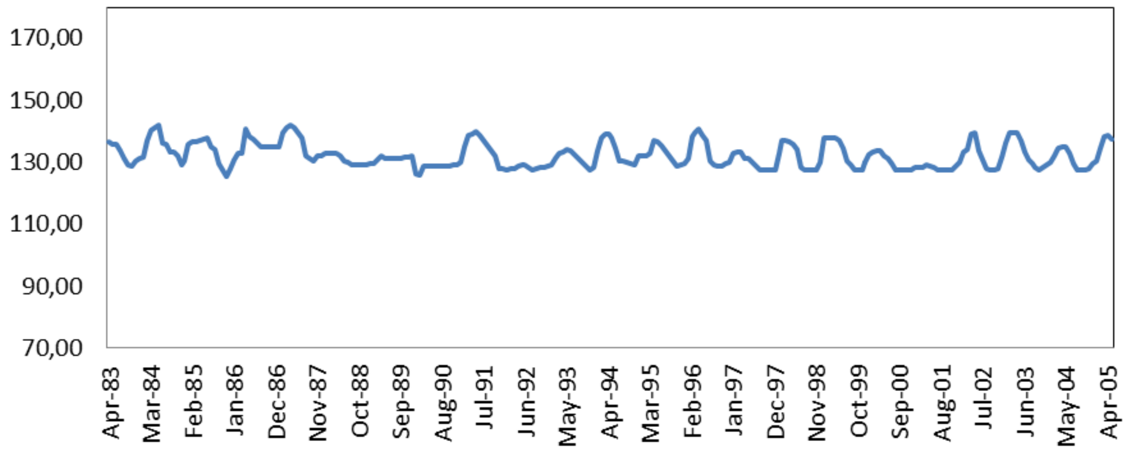

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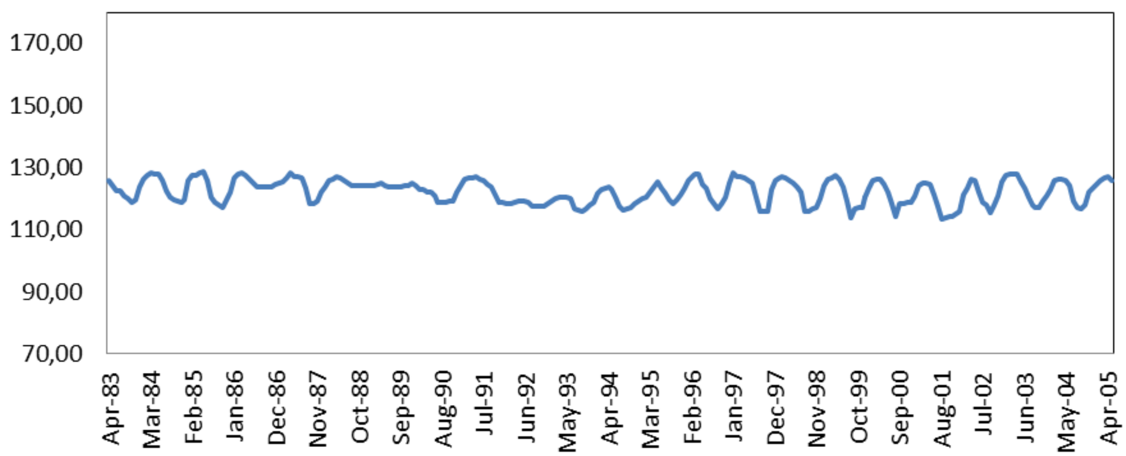

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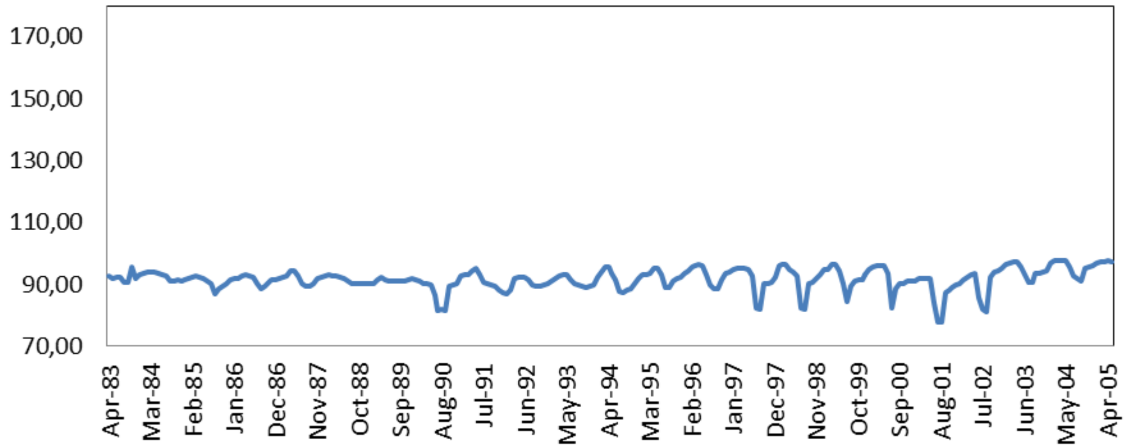
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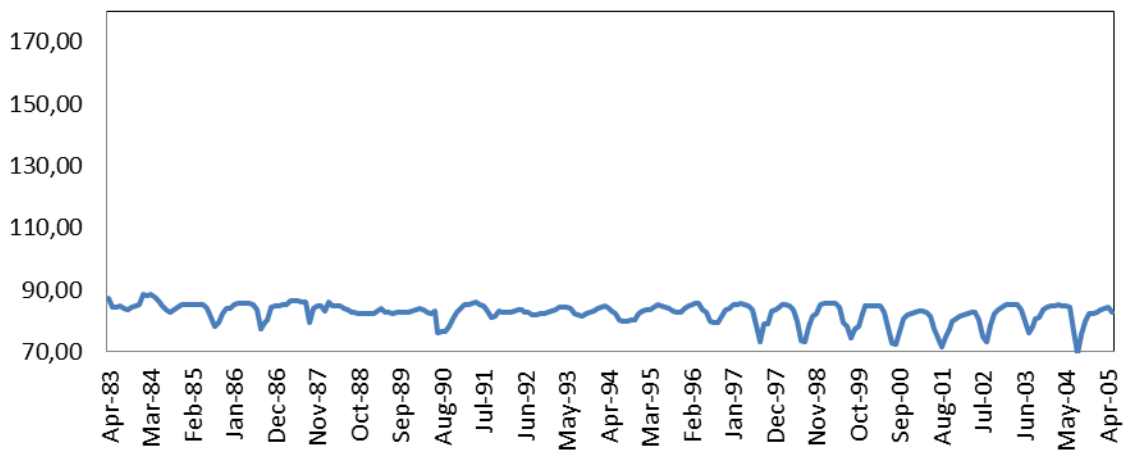
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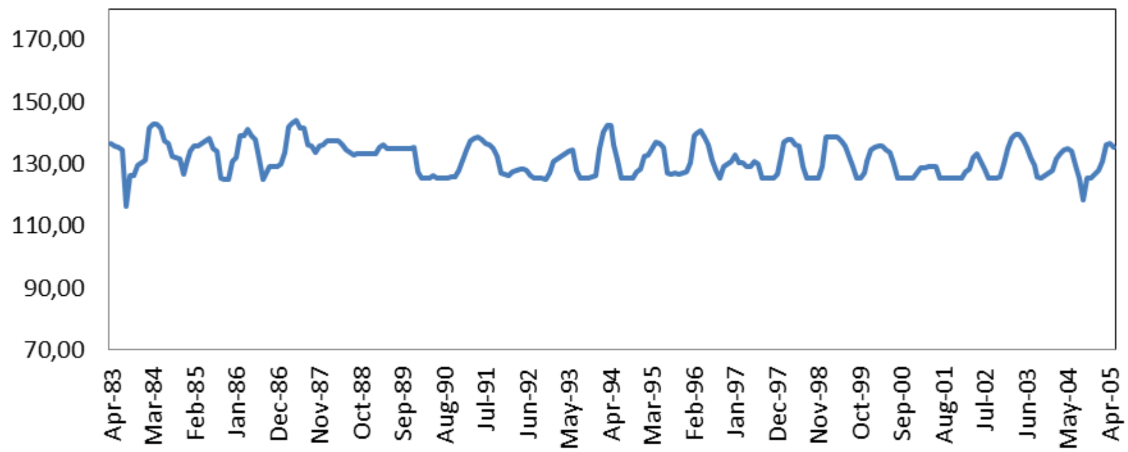
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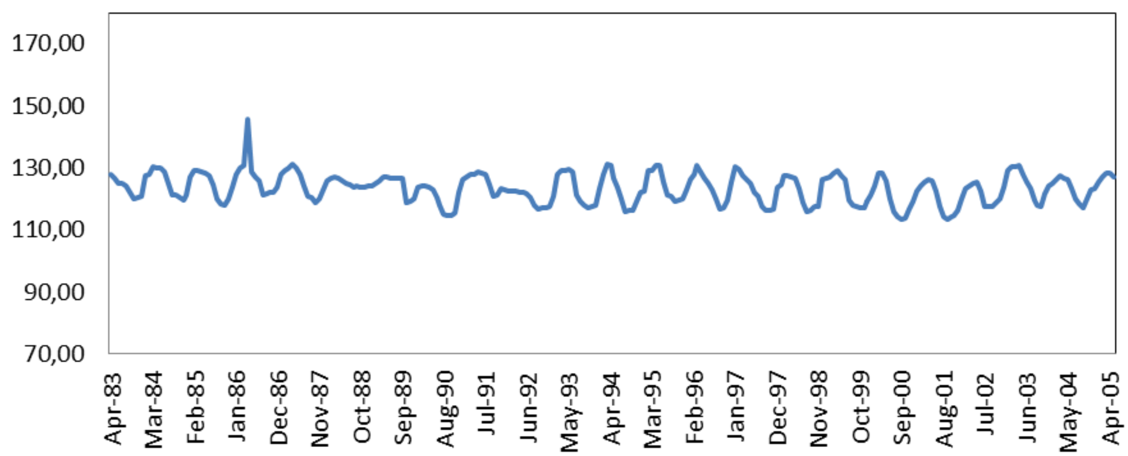
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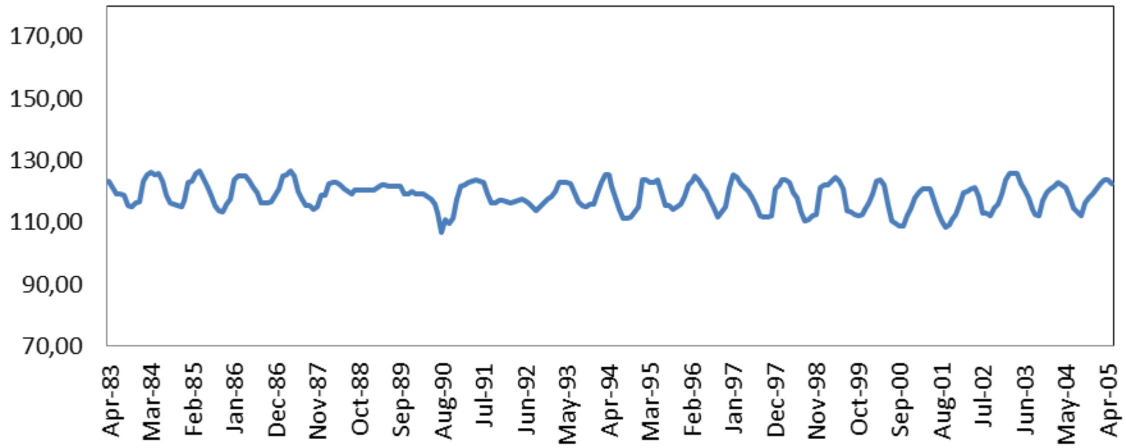
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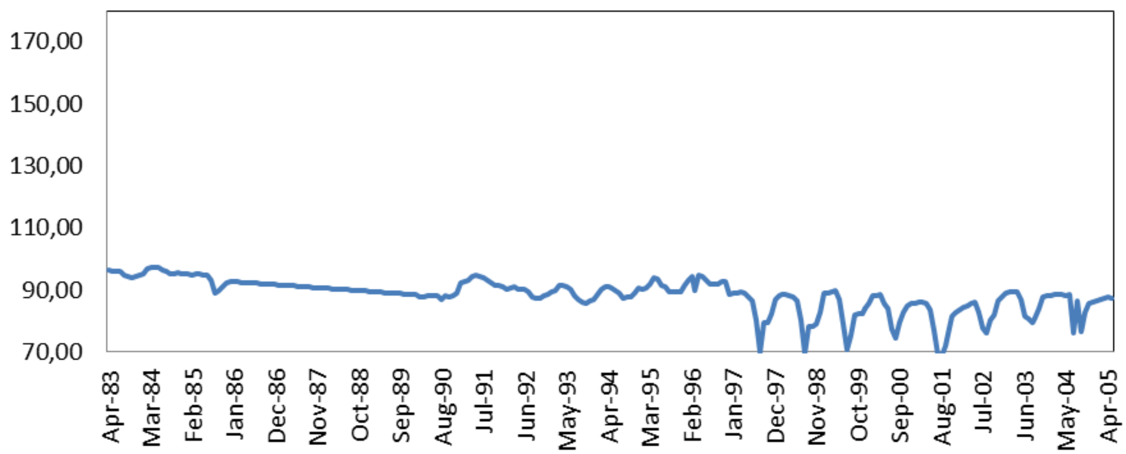
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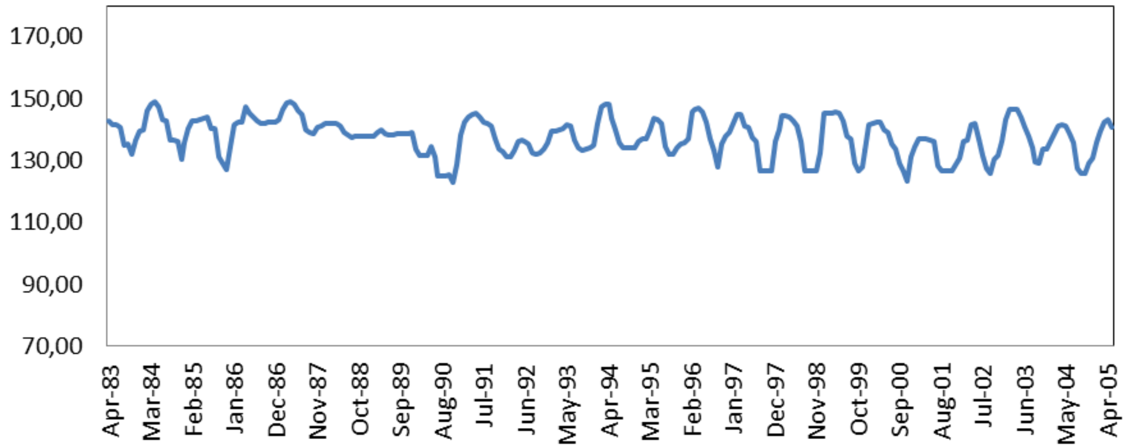
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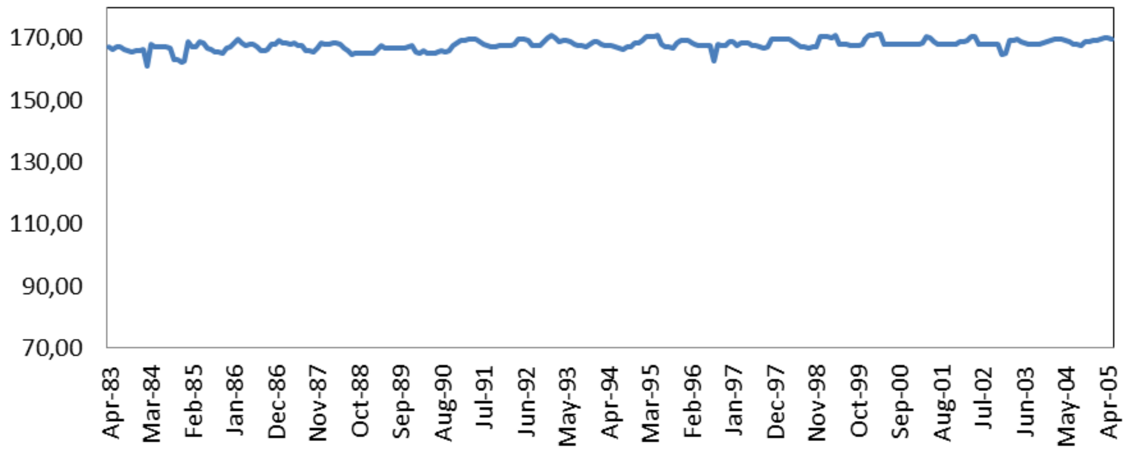
TRIKALA_PC2



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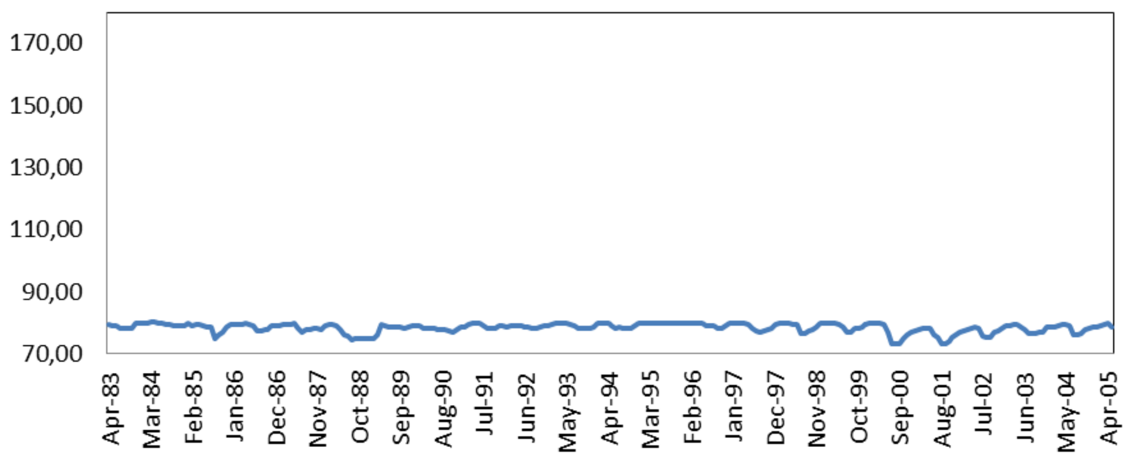

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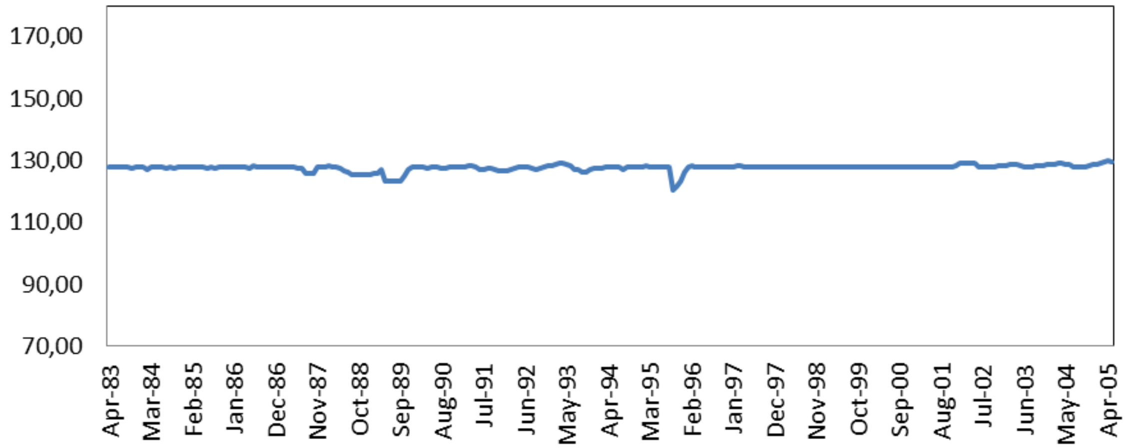
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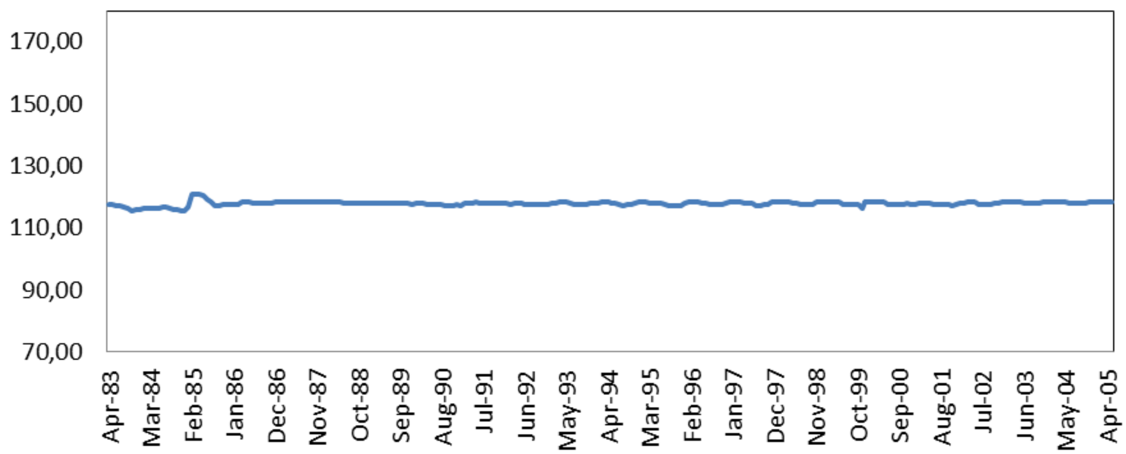
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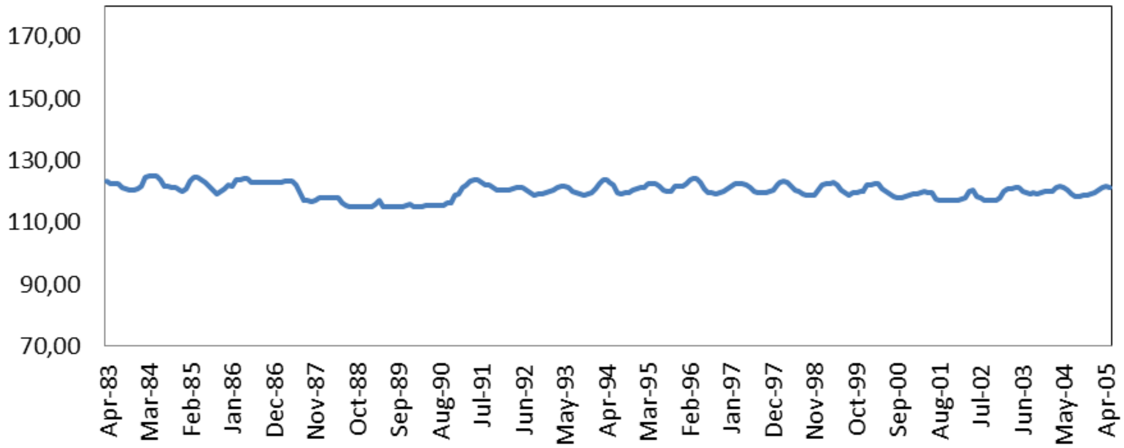
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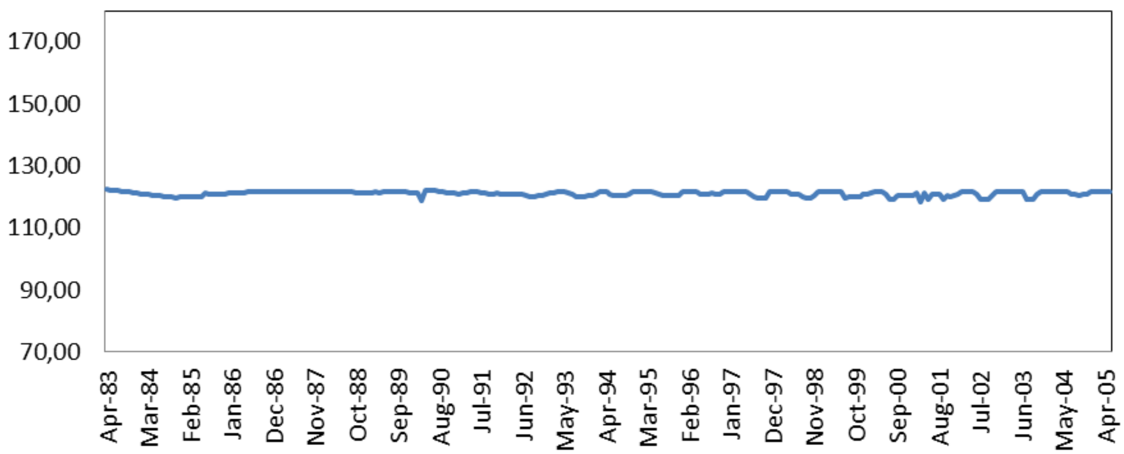
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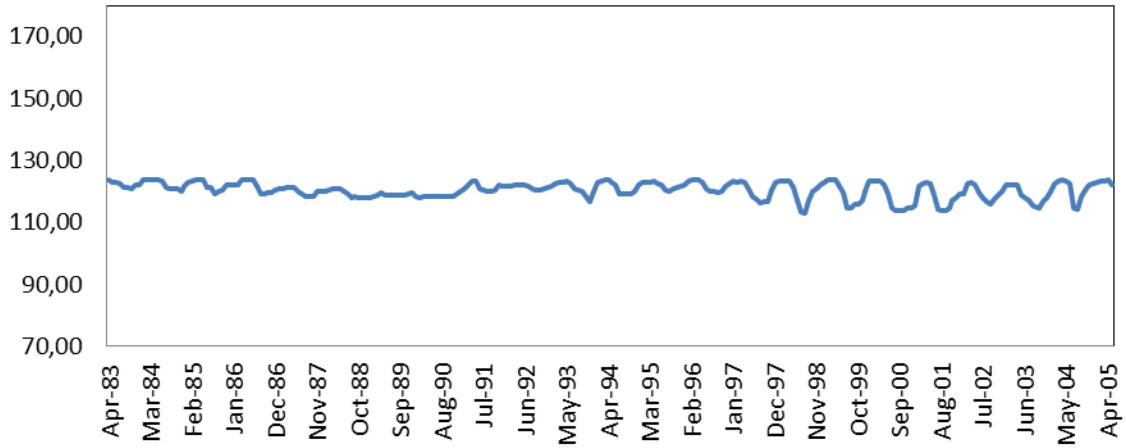
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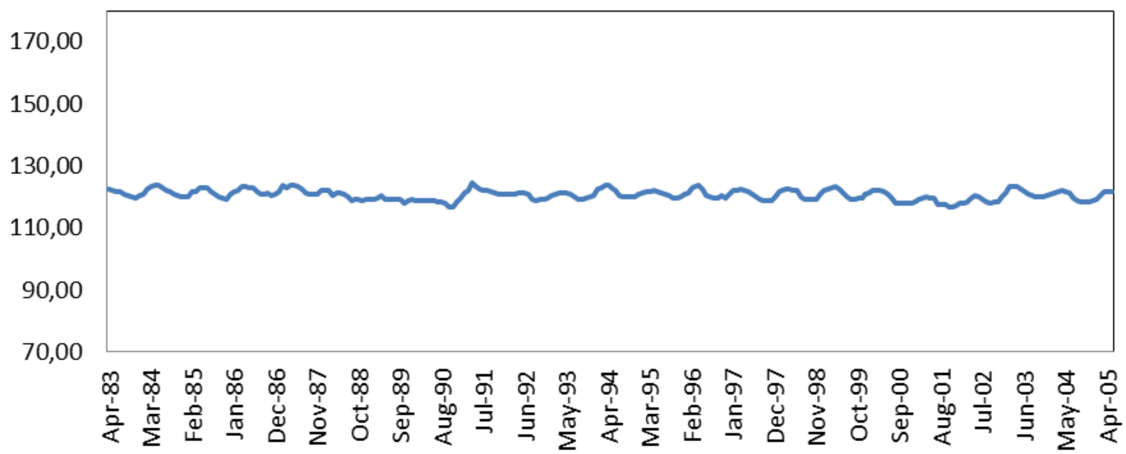
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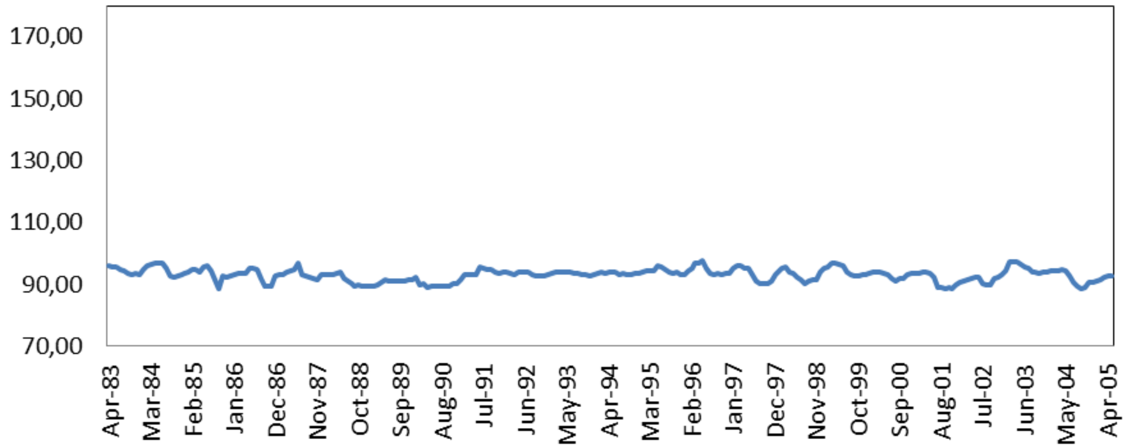
D5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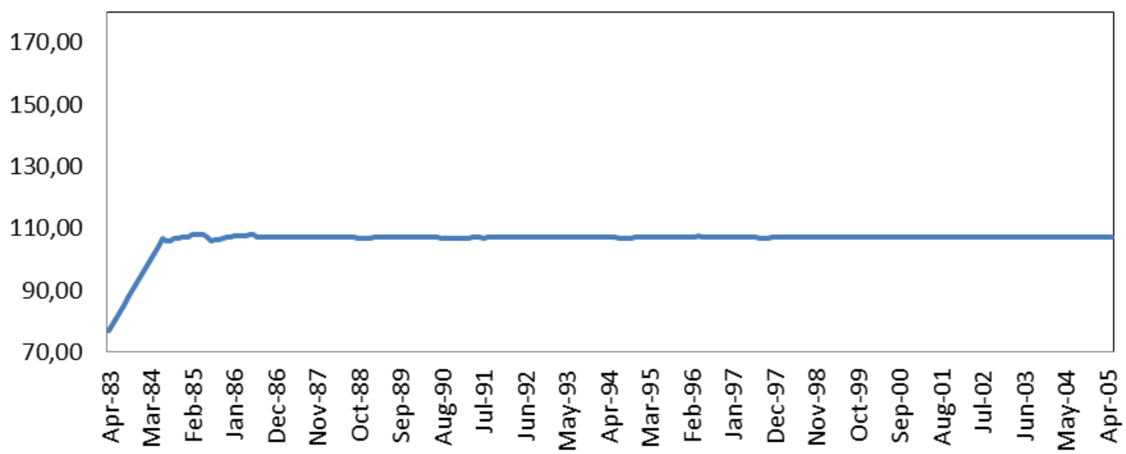
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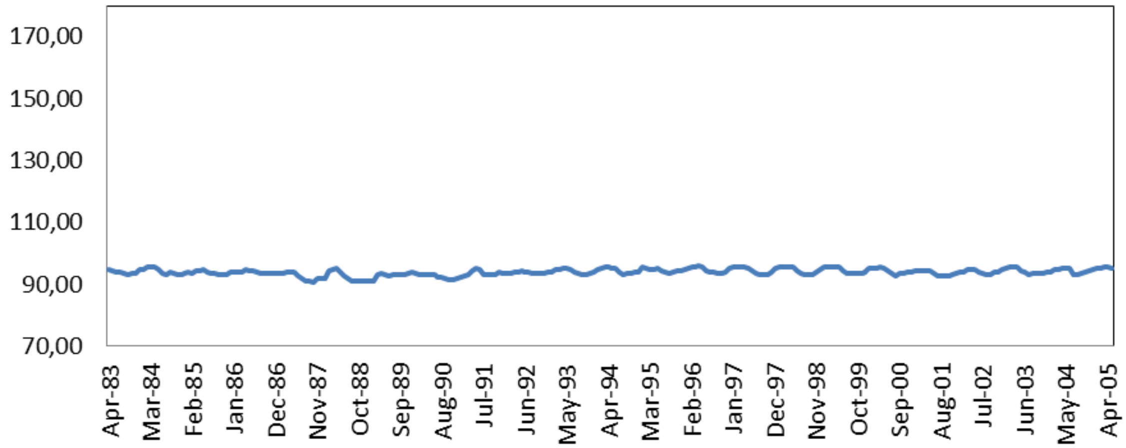
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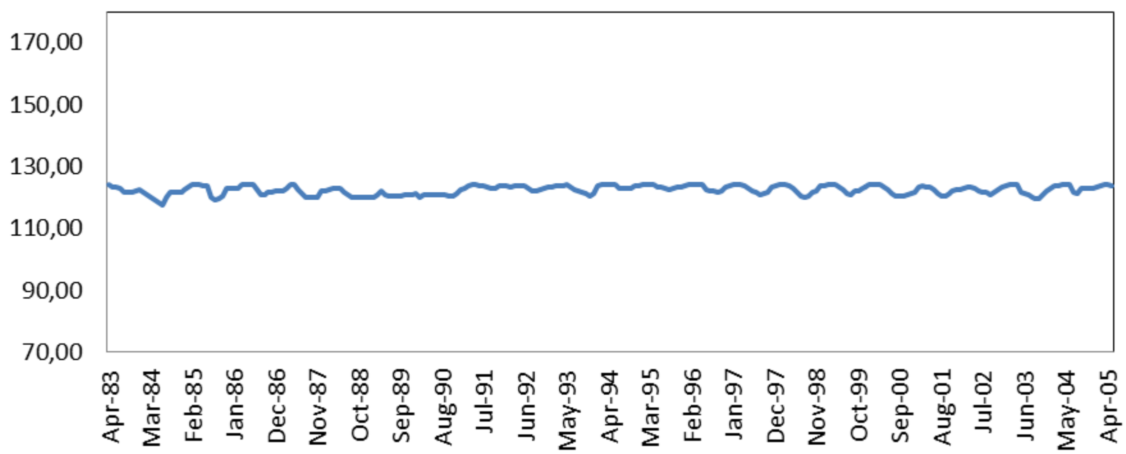
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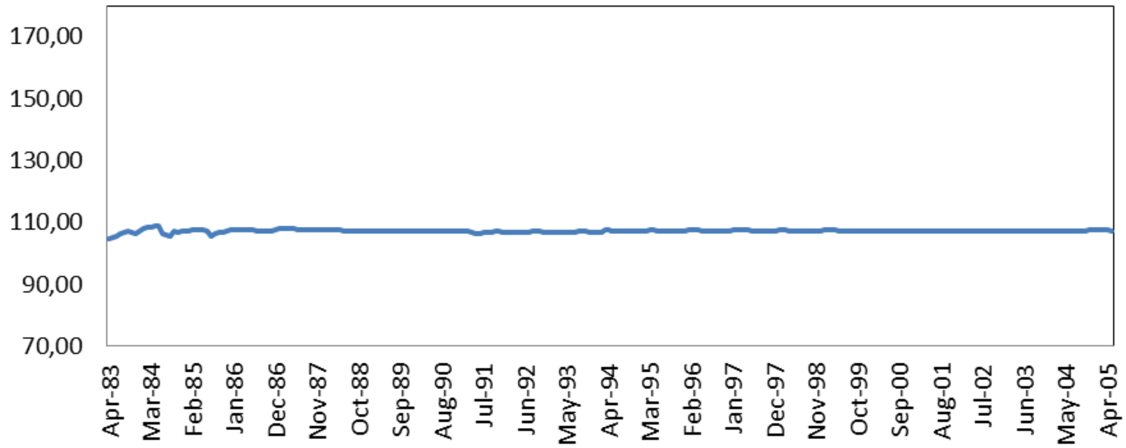
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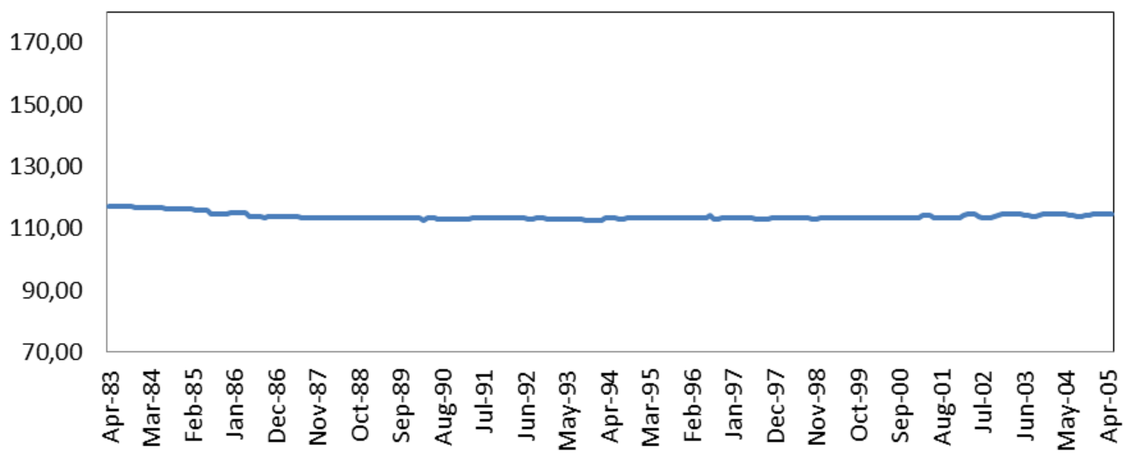
PZ1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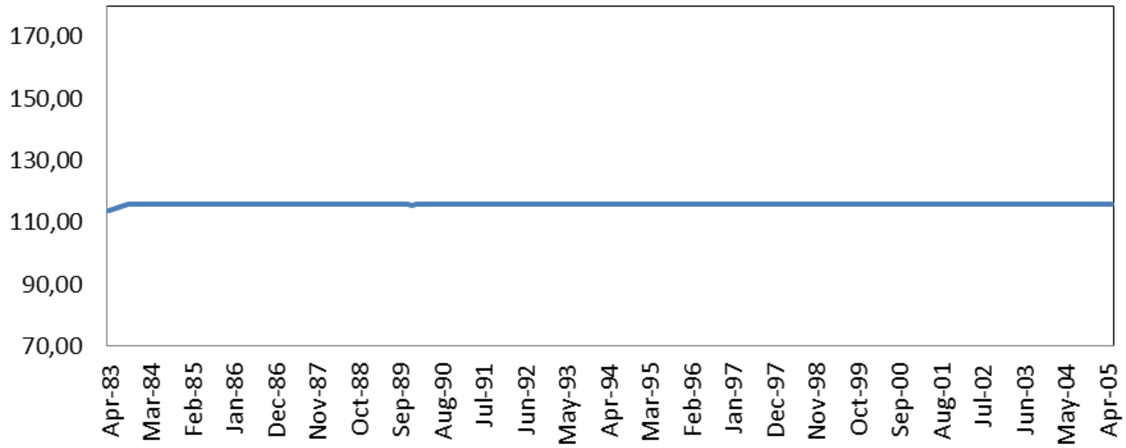
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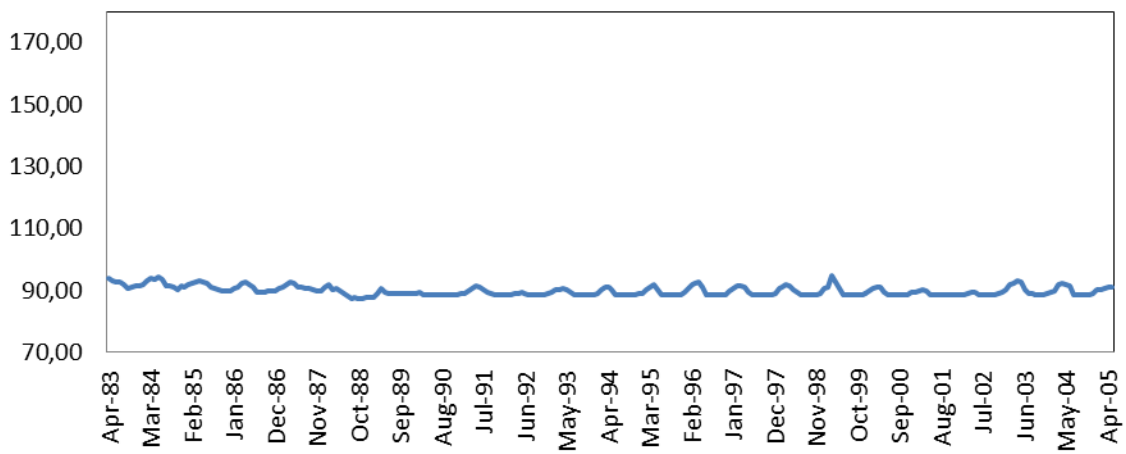
PZ3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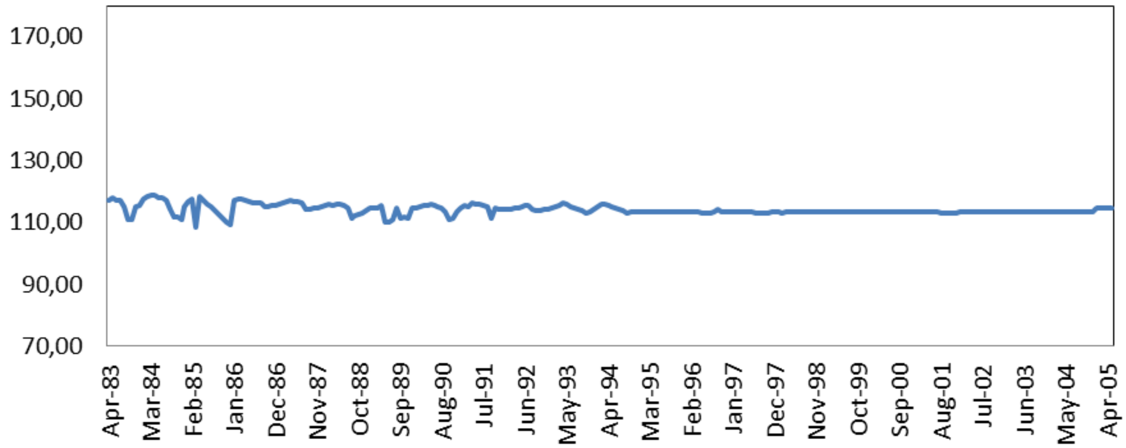
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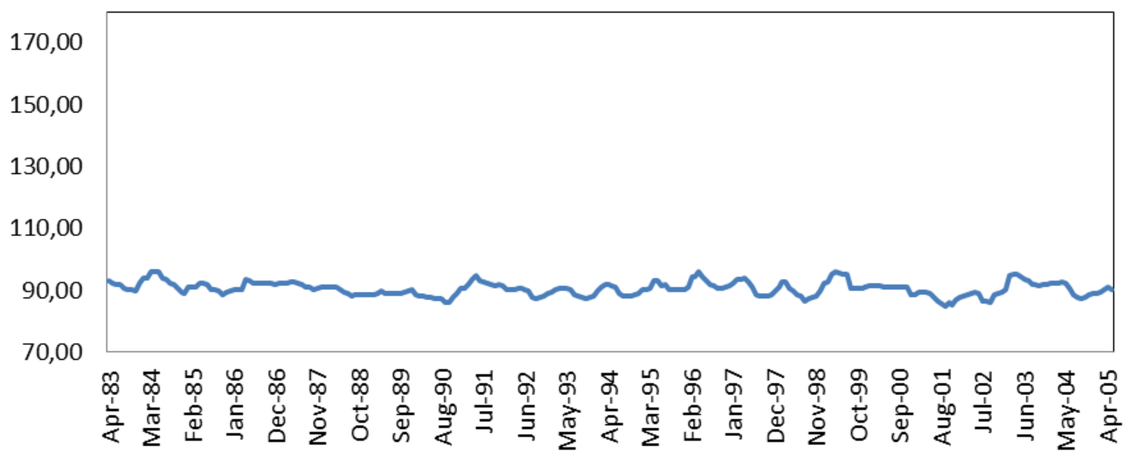
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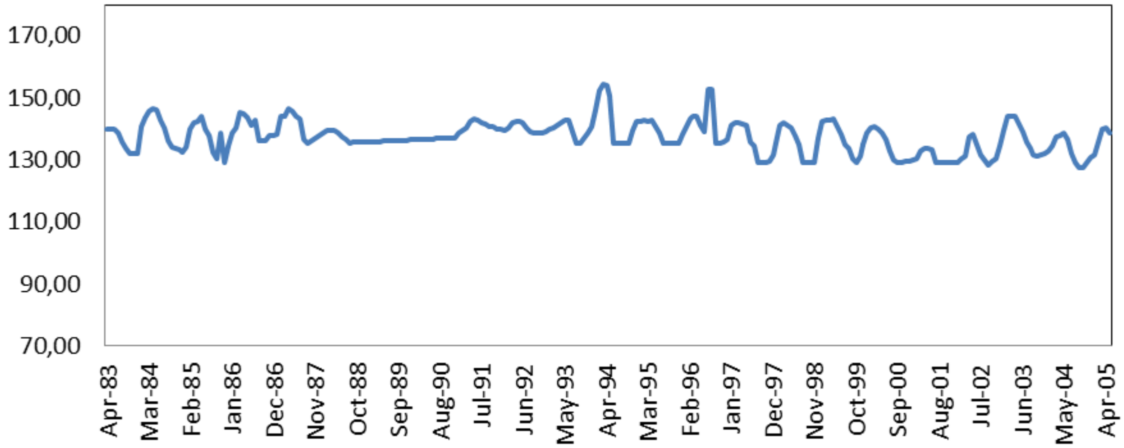

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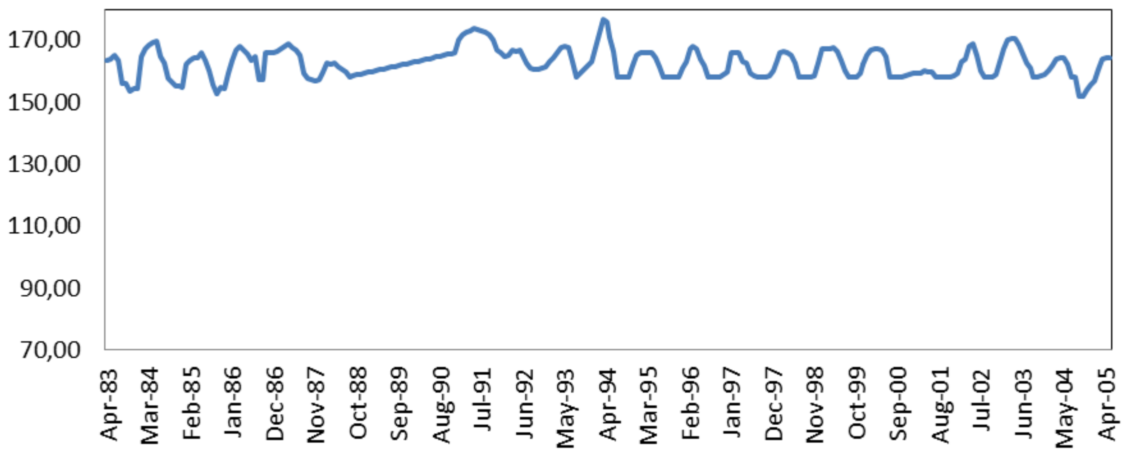

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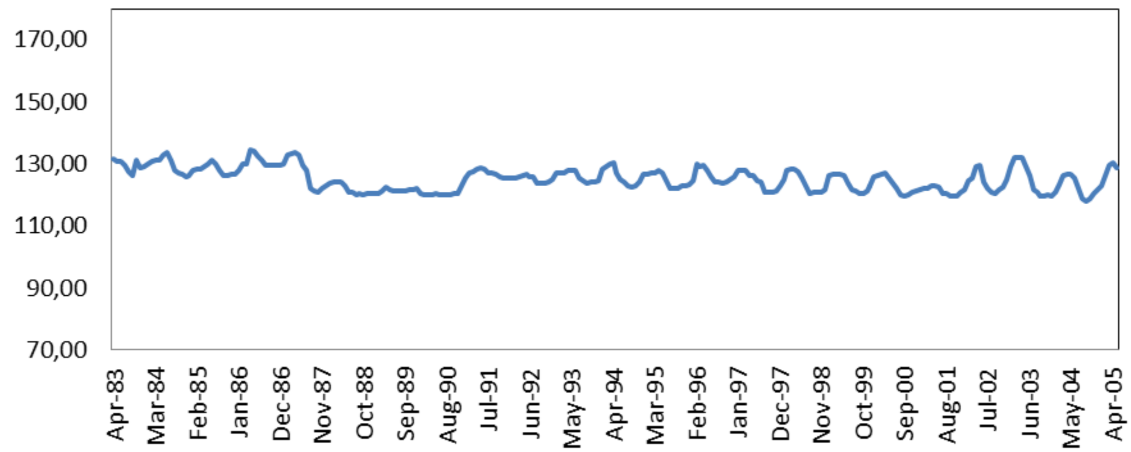

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