12

Instrumentation for Measurement of Laboratory and *In-Situ* Soil Hydraulic Conductivity Properties

Jose Antonio Gutierrez Gnecchi et al.*
[1]*Instituto Tecnológico de Morelia, Departamento de Ingeniería Electrónica*
México

1. Introduction

Measurement of soil hydraulic conductivity properties is very important for soil characterization, modelling of water transport and waste contaminant migration through soil, management of soil organic matter and management of water resources. Moreover, measurement of hydraulic properties is also important for developing strategies to increase crop productivity, and 3-D modelling of water migration properties to predict groundwater and aquifer recharge. Amongst the most common methods, used in laboratory and field test trials to determine the properties of water propagation through soil, are measurement of hydraulic conductivity and wetting front detection. However since the hydraulic conductivity properties vary considerably from region to region (and even for the same region and type of soil) numerous and diverse methods are continuously reported that fit particular needs. Despite the large number of methods and apparatus reported, and commercially available instruments for measuring the dynamics of water propagation through the soil, it is still necessary to continue developing new and improved instrumentation systems to increase the quality and quantity of reliable information and reduce systematic errors. In addition, commercial instruments may only be available from foreign distributors. Thus the use of imported technology, with little or no technical support locally, and the added import tax costs result prohibitive for the average producer and precludes the use of electronics instrumentation by producers without a technical background. Since 77% of the water in Mexico is used in agriculture, the availability is scarce in many wide areas, and the water usage efficiency is low, the situation becomes more critical due to the demand for increased productivity. Undoubtedly, research and development activities in higher education institutions should have scientific, technological, social and economical impact in the surroundings. This chapter presents the results of the cooperation between ITM-Electronics Engineering Department (*Spanish: Instituto Tecnológico de Morelia*), INIRENA-Research Centre for Natural Resources Studies (*Spanish: Instituto*

* Alberto Gómez-Tagle (Jr)[2], Philippe Lobit[3], Adriana Téllez Anguiano[1], Arturo Méndez Patiño[1], Gerardo Marx Chávez Campos[1] and Fernando Landeros Paramo[1]
[1]*Instituto Tecnológico de Morelia, Departamento de Ingeniería Electrónica, México*
[2] *Instituto de Investigaciones Sobre Los Recursos Naturales, Laboratorio de Suelos, Michoacán, México.*
[3] *Instituto De Investigaciones Agropecuarias y Forestales, México*

Nacional de Investigación Sobre Los Recursos Naturales) and IIAF (*Spanish: Instituto de Investigaciones Agropecuarias y Forestales*) to develop instrumentation for measuring some of the properties that govern the dynamics of water propagation through soil.

1.1 Water usage in Mexico

Water resources in Mexico are considered essential for national security. Urban, industrial and agricultural conservation of the environment, economic and social development depend on the rational management of water resources. In Mexico, the surface dedicated to agriculture is approximately 21 million hectare (*abbreviation ha*) (10.5% of the national territory) of which 6.46 million ha are irrigated zones and 14.5 million ha are rainfed zones. Most of the fresh water resources are dedicated to agriculture, where the 77% is allocated for consumptive use (Table 1).

USE	ORIGIN		TOTAL VOLUMEN	PERCENTAGE OF EXTRACTION
	SUPERFICIAL	SUBTERRANEAN		
Agriculture[1]	40.7	20.5	61.2	76.8
Public Water Supply[2]	4.2	7.0	11.2	14.0
Self sustained industry[3]	1.6	1.6	3.3	4.1
Thermoelectric	3.6	0.4	4.1	5.1
TOTAL	50.2	29.5	79.8	100.0

1 km^3 = 1 000 hm^3 = 1 thousand of millions of m^3.
Data correspond to volume allocated through to December 31 of 2008
[1] Includes agriculture, livestock, aquaculture, and other, according to the REPDA-CNA (Public Rights Register of Water- National Water Commission) classification. Includes 1.30 km^3 of water corresponding to irrigation districts pending registration.
[2] Includes urban public and domestic uses according to the REPDA-CNA classification.
[3] Includes industrial agro industrial, commerce and services according to the REPDA-CNA classification.
Source: National Water Commission (CONAGUA: http://www.cna.gob.mx).

Table 1. Consumptive use of water in Mexico according to the source of origin. (Thousands of millions of cubic metres, km^3)

The Free Trade Agreement of North America and the globalization of markets and the economy, impose more demands on Mexican producers to increase efficiency and quality of agricultural production, optimizing the use of resources in a sustainable manner. Now it is necessary to produce more, with better quality and lower costs to meet local demand, compete with imported agricultural products and eventually to produce products that meet the quality standards that exist in international markets (weight, size, color and texture). As part of Mexico's National Water Program 2007-2010 (Mexican National Water Commission, *Spanish: Comision Nacional del Agua* [CONAGUA], 2008) it is proposed that the use of technology for irrigation modernization would increase water productivity by 2.8% annually, measured in kilograms per cubic meter of water used in irrigation districts, going from 1.41 in 2006 to 1.66 in 2012, and will result in greater benefit to producers. At the same time, it is also proposed that the reduction of energy consumption will lead to achieve a more efficient use of water. However, it is common that the term "technification" generally corresponds to hydraulic infrastructure for drainage of surplus water. Although it has been reported (Mexican National Water Commission, *Spanish: Comision Nacional del Agua* [CONAGUA], 2010) that technification of agriculture has increased by 50% nationwide, compared to 2000, the reports do not specify what level or type of modernization is done, and generally consists of pumping equipment and/or hydraulic installations for the evacuation of excess water. To a lesser extent, the use of agro-meteorological stations is also included as part of efforts to introduce technology to the field. However, it is necessary to increase the level of modernization of the Mexican countryside in order to achieve precision agriculture practices at regional and national levels.

1.2 Soil hydraulic conductivity

Soil water infiltration is a process by which water propagates from the soil surface, inwards, through the porous media. One of the properties that govern the rate of propagation of water through the soil is hydraulic conductivity, which in turn, depends on a number of factors such as soil content and texture (Das Gupta et al., 2006), vegetation root hardness (Rachman et al., 2004; Seobi et al., 2005), soil preparation (Park & Smucker, 2005), chemical content (Schwartz & Evett, 2003), soil temperature and weather conditions (Prunty & Bell, 2005; Chunye et al., 2003), stability and continuity of the porous system (Soracco, 2003), including macro (Mbagwu, 1995), meso (Bodinayake et al., 2004) and microporosity (Eynard et al., 2004). Amognst the methods reported for studying the hydraulic properties of soils, the infiltrometer and permeameter are probably the most commonly used devices in field (Angulo-Jaramillo et al., 2000) and laboratory tests (Johnson et al. , 2005) respectively. Other methods used for characterizing soil hydraulic properties reported are heat-pulse soil water flux density measurements (Kluitenberg, 2001), electromagnetic measurements (Dudley et al., 2003; Seyfried & Murdock, 2004), radiation-based measurements (Simpson, 2006) image analysis (Gimmi & Ursino, 2004) and multimodal instruments (Pedro Vaz et al., 2001; Schwartz & Evett, 2003) that permit measurement of several variables simultaneously. The infiltrometer is a very popular instrument among researchers (Fig. 1A), because knowledge of soil hydraulic properties is a key factor in understanding their impact on hydrological processes such as infiltration (Esteves et al., 2005) the superficial flow and aquifer recharge. Basic infiltrometers are relatively simple devices, which essentially consist of a reservoir (fitted with a graduated scale), a metallic ring (single or double) partially inserted into the soil, and a stop valve. A test is conducted by allowing the liquid to exit the container, either directly or through a pipe into the ring, measuring the rate of water infiltration while maintaining a small positive pressure on the fluid. The infiltration process consists of two main parts: the transient and steady state (Fig. 1B). The transient state occurs from the beginning of the experiment up to the time when a constant rate of water infiltration is attained.

Once the soil sample is saturated with water, the constant pressure maintains a constant infiltration rate. Hydraulic conductivity can then be calculated using the entire data set (Wu1 method) (Wu & Pan, 1997) or the data corresponding to the steady state phase (Wu2 method) (Wu & Pan 1999) by measuring the slope of the resulting curve. However, recording the infiltration process data from direct, visual measurements is a highly demanding task, both, in time and economic resources; data has to be recorded in time intervals between 1 to 5 minutes in elapsed times ranging from 0.5 to 4 hours. Many authors

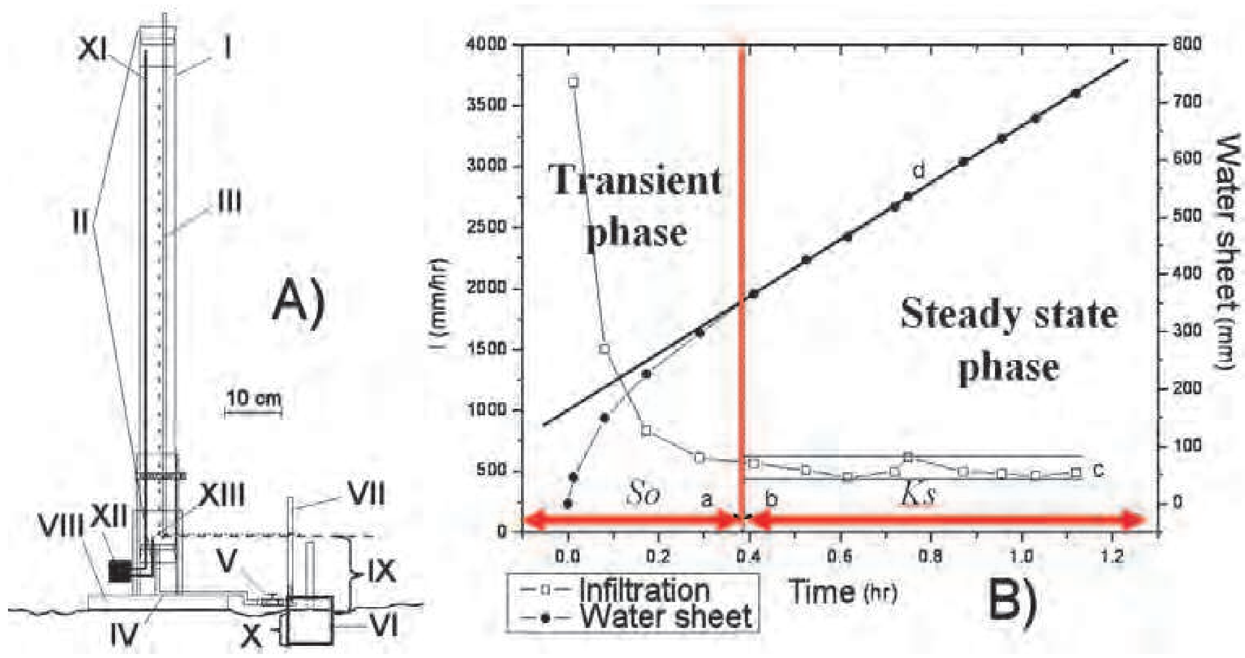


Fig. 1. A) Schematic diagram of an infiltrometer. I) Main reservoir (Mariotte), II) rubber stoppers, III) bubbling tubing, IV) water outlet, V) stop valve, VI) metallic ring, VII) purge and measurement of hydraulic load, VIII) stand base, IX) constant hydraulic load, X) insertion depth, XI) pressure sensor access to air chamber, XII) data logger, XII) pressure sensor access to the water column. B) Classical infiltration data results showing the transient and steady state phases of the infiltration process.

acknowledge the need for instrumentation and data recording devices (infiltrometer and permeameter) to automate the data acquisition, minimize human errors and reduce the time spent in taking measurements (Amezketa-Lizarraga et al., 2002; Johnson et al., 2005). Therefore many devices have been reported and patented since the 1940s (Bull, 1949) to try to automate the data acquisition process. Automated devices rely on data recording units (data loggers). However the main constraint is the local availability of such equipment, followed by cost. In many cases researchers implement their own devices without automation, such as a double ring infiltrometer (Carlon-Allende, 2006). Automating an infiltrometer requires accurate measurement of the change of height of the water column over time, as the water is allowed to exit the container. Some of the methods used for measuring the column height are the use of paired infrared sensors in a plastic cylinder (Wilson et al., 2000), float valve system with meter spool ring infiltrometer (Amezketa-Lizárraga et al., 2002), Time domain reflectometry (TDR) infrared detectors and float sensor or pressure sensors (Ankeny et al., 1988). The use of pressure transducers is probably the most common choice because of low-cost, simplicity, easy implementation and reliability. Overman et al. (1968) reported the application of pressure transducers since the mid 60s, to implement a variable load laboratory infiltrometer, designed specifically for low-permeability materials. Constanz & Murphy (1987) generated a system that could measure the height of a column of water from pressure changes in a Mariotte reservoir and thus infer the infiltration data. Their instrument used Transamerica CEC 4-312 pressure transducers, with pressure range ± 12.5 psi. The automated device allowed rapid data acquisition with minimal supervision. Ankeny et al. (1988) reported that the use of one transducer produced measurement errors due to bubbling inside the container and adapted the design of Constanz & Murphy (1987) to a tension infiltrometer (disc) with two PX-136 transducers with measurement range 0-5 PSI (Omega Engineering, Stanford, CT) and a 21X Campbell data logger (Campbell Scientific, Inc.). The resulting scheme using two transducers required precise timing, but minimized the variability generated by bubbling and reduced the standard deviation from 6.2 mm (single transducer) to 2.2 mm. Prieksat et al. (1992) used the two-transducer design in a single ring infiltrometer, to register data from multiple locations simultaneously, facilitating the characterization process. Casey and Derby (2002) used a differential pressure sensor (PX26-001DV, Omega Engineering, Stanford, CT) and evaluated the device in the field, achieving 0.05 mm standard deviation. The authors noted that the improvement in resolution might not change significantly the estimation of soil hydraulic properties, but could be useful when data are processed as exponential relations methods such as Ankeny (1992) or Reynolds and Elrick, (1991). Johnson et al. (2005) constructed six laboratory variable load permeameters, using pressure sensors PX236 (Omega Engineering) and perspex tubes, to work with undisturbed samples, using a data logger programmed to record readings at regular intervals. The comparison with the manual method showed no significant differences for texture analysis. Špongrová (2006), designed, built and tested a fully automated tension infiltrometer, that included both the measurement of water level and the control of the voltages applied, using a Honeywell differential pressure transducer with range 0 to 5 PSI (0 to 34.4 kPa), connected to a Campbell 21X datalogger (Campbell Scientific Inc.) and a laptop. The results showed that the equipment reduced the monitoring time, increasing the number of test trails per day. Although there are several commercial devices, such as manual or automated tension infiltrometers they generally depend on external data logger units.

2. Case study 1: Automated infiltrometer using a commercial data logger

One of the preferred methods for measurement the height changes of the water column involves the use of pressure transducers. Therefore, it is necessary to implement an instrumentation and data acquisition system that can be used to gather information of the infiltration process for off-line signal processing. Fig. 2 shows the classic data acquisition scheme used. The instrumentation scheme consists of a pressure transducer, a signal conditioning and amplifier stage, and a digitizing unit with data storage capabilities for transferring the measurements to a host computer. To allow some level of autonomy, and ease of use, it is necessary to use low-power, versatile analogue and digital devices.

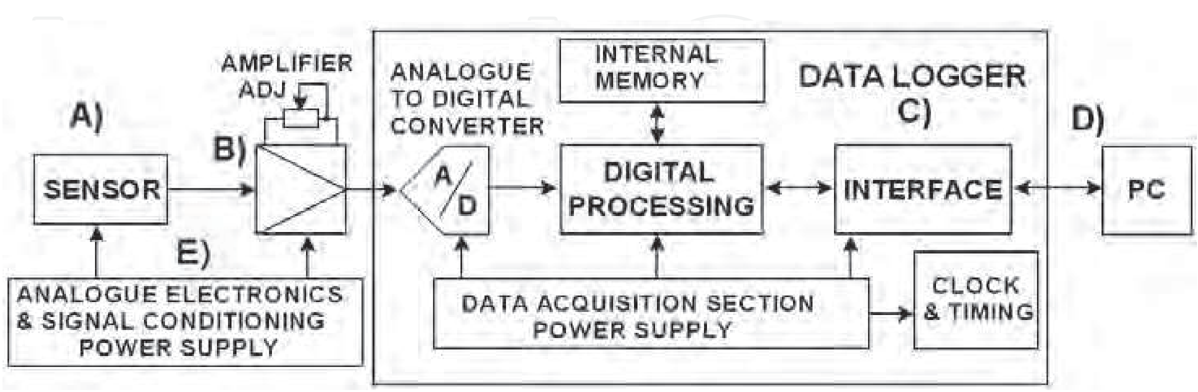


Fig. 2. Block diagram of the instrumentation and data acquisition system used for automating soil water infiltration measurements. A) Pressure sensor, B) instrumentation amplifier, C) data logger including analogue to digital converter, internal memory, interface circuitry and power supply for transferring data to D) a PC. E) Power supply circuit for the analogue electronics section.

Fortunately, the advances in electronics technology over the last two decades have resulted in a number of components that can be obtained from local and international distributors to build the analogue and signal conditioning circuitry. As to the digitizing section, a number of data logger units are commercially available with impressive operating characteristics. The case study presented in this section is based on the choice of a low-cost data acquisition unit.

2.1 Data logger

One particular low-cost, simple-to-use device is the EL-USB-3 data logger from Lascar Electronics (Fig. 3).

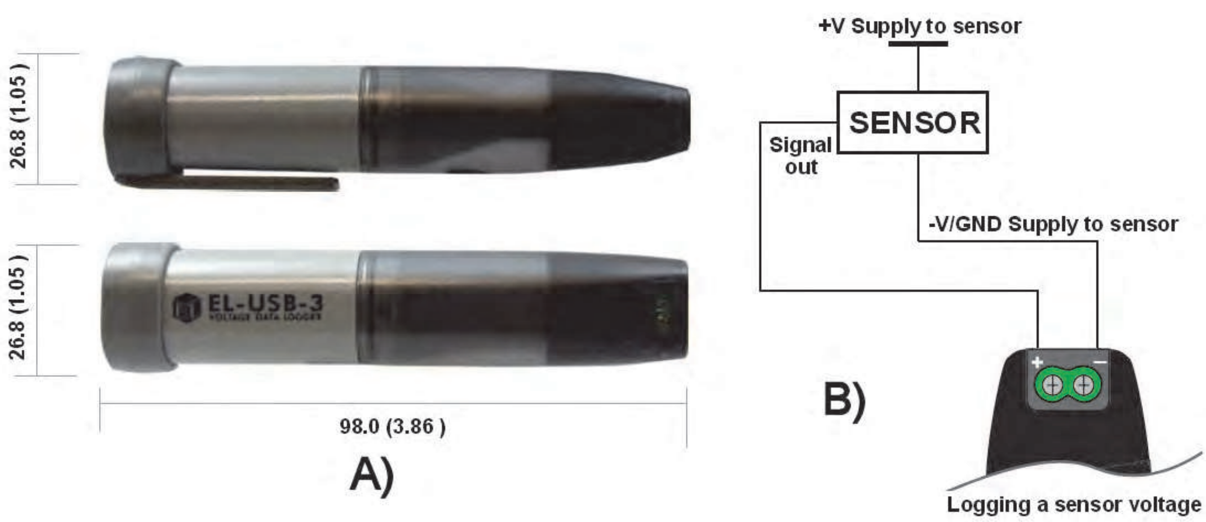


Fig. 3. EL-USB-3 Voltage data logger from Lascar Electronics. A) Physical dimensions and B) typical connection for logging sensor signals. Reproduced with permission. Copyright 2011 Lascar Electronics. All Rights Reserved from Lascar Electronics.

The EL-USB-3 is a stand-alone data logger powered internally by a 3.6 Volts battery, capable of taking 32,510 readings in the range of 0-30 Volts with 50 mV resolution. The signals are applied to the data logger through a detachable cap, so that it can be removed from the instrumentation electronics for programming and data transfer without disconnecting wires. The data logger includes a USB interface for setting the data acquisition sampling rate from 1 second to 12 hours (1 second, 10 seconds, 1 minute, 5 minutes, 30 minutes, 1 hour, 6 hours and 12 hours) and also for transferring the results to a host PC. The operation can be assessed by observing the activity of two LEDs, red and green, which are included (Fig. 4).
Once the test has concluded, the measured data can be transferred to a host PC for off-line analysis through the USB interface using the software included. Thus the EL-USB-3 includes all the necessary components shown in Fig. 2C corresponding to the digitizing section of the instrumentation scheme proposed. Using a commercial data logger reduces instrumentation development time. Nevertheless, the signal conditioning section must consider the operating characteristics of the data logger to maximize the measurement resolution. That is the voltage corresponding to the maximum height of the water column (100 cm) must be +30V.

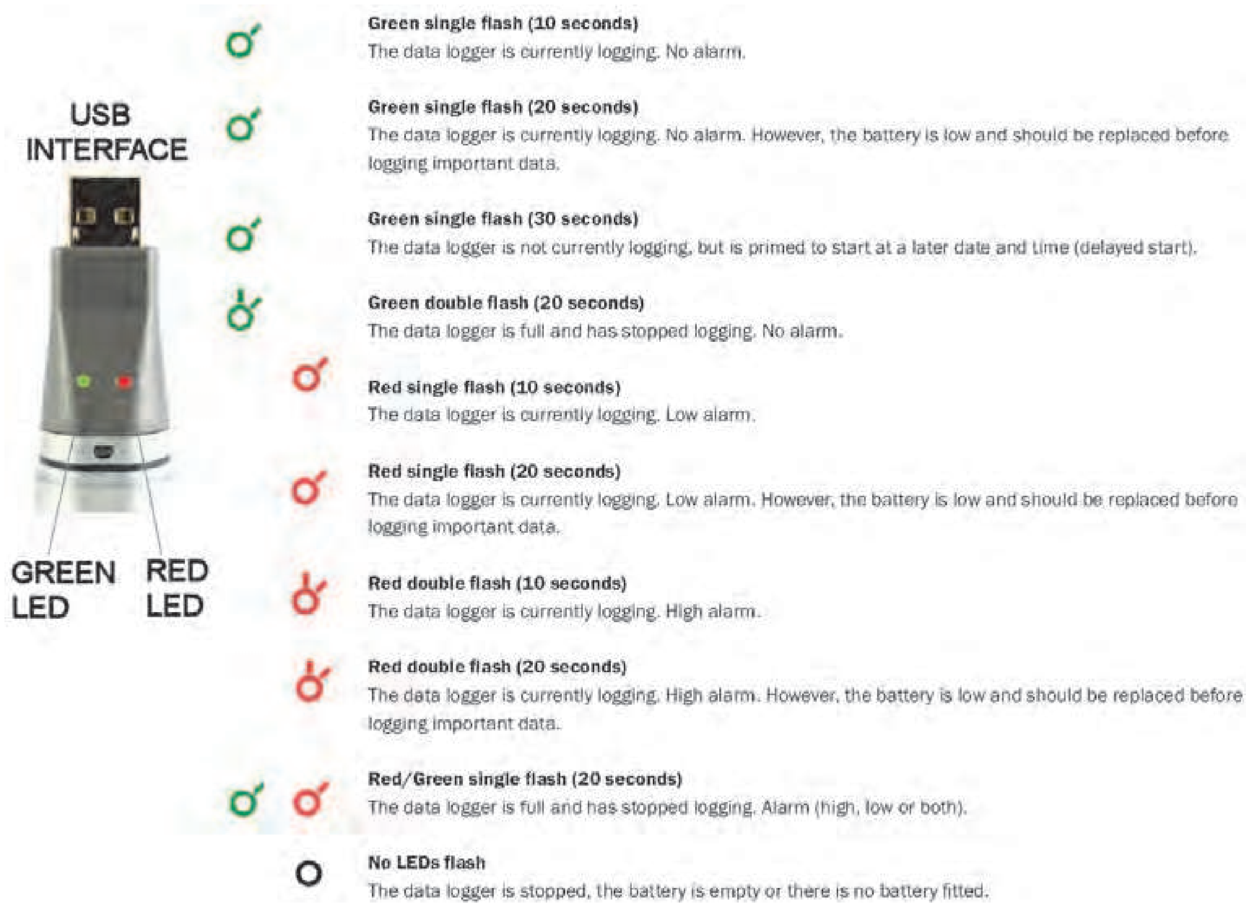


Fig. 4. Data logger USB connector and operation assessment depending on the LED activity. Reproduced with permission. Copyright 2011 Lascar Electronics. All Rights Reserved

2.2 Power supply

The first step in developing the instrumentation circuitry consists of obtaining a little over +30V from a +9V battery, because interfacing with the data logger requires that the analogue instrumentation operate with a voltage slightly over 30V. The circuit must be small and must consume very little current from the battery. Fig. 5 shows the block diagram of the power supply.

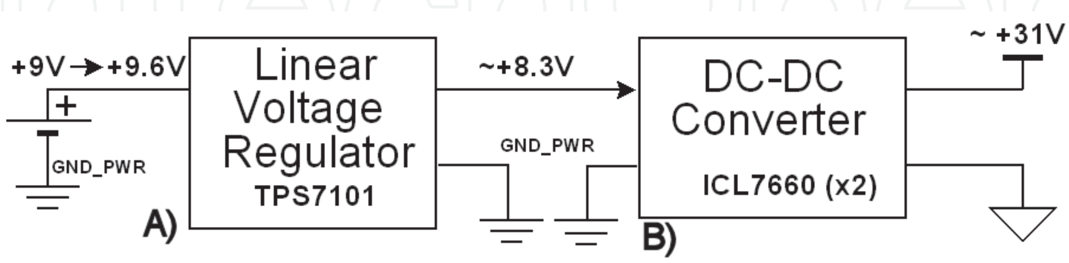


Fig. 5. Block diagram of the power supply. A) The battery feeds a linear voltage regulator. B) the output from the regulator is increased to (over) +30 V to power up the instrumentation amplifier.

The battery feeds a low dropout, adjustable linear regulator (TPS7101 from Texas Instruments©) which provides the regulated supply voltage to the DC/DC converter (Fig. 6).

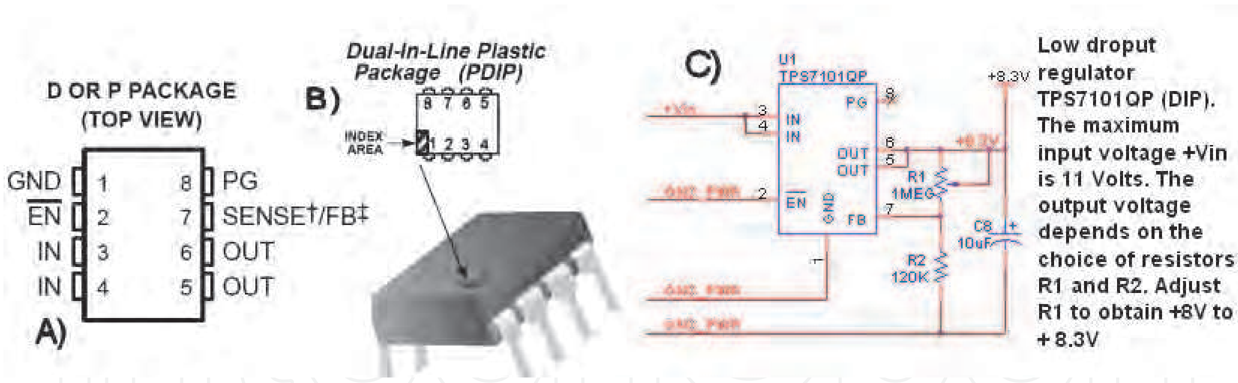


Fig. 6. A) Description of the TPS7101 (linear low dropout regulator) terminals. B) Identification of the index area (terminal 1). C) Regulator diagram. Copyright Texas Instruments©. All Rights Reserved.

The TPS7101 output voltage is adjusted to +8.3V by trimming R1 which is a 1 MegaOhm, 20 turns, trimming potentiometer. R2 is a fixed value ¼ Watt precision, metal film resistor. C8 is a tantalum capacitor, and is used for filtering the output and provides stability to the voltage regulator. The TPS7101's output feeds the DC/DC converter formed by the two ICL7660 integrated circuits from Intersil © (U2 and U3) (Fig. 7B). The ICL7660 is a low-power monolithic CMOS power supply that can be configured easily to double the input voltage and also to provide complimentary negative voltage, requiring a minimal amount of non-critical passive components. In this application, U2 is configured to perform two operations: U2 inverts the input voltage and also doubles the positive input. The circuit uses low forward-voltage-drop Schottky diodes to reduce the effect of the voltage drop across the circuit. Another feature of the ICL7660 is that it can be cascaded to increase the differential voltage. Thus, U3 is configured to double the negative voltage obtained from U2. In effect, the array of U2 and U3 increases the regulated voltage from the TPS7101 to approximately 31 Volts, enough to provide the energy for the instrumentation amplifier and pressure sensor.

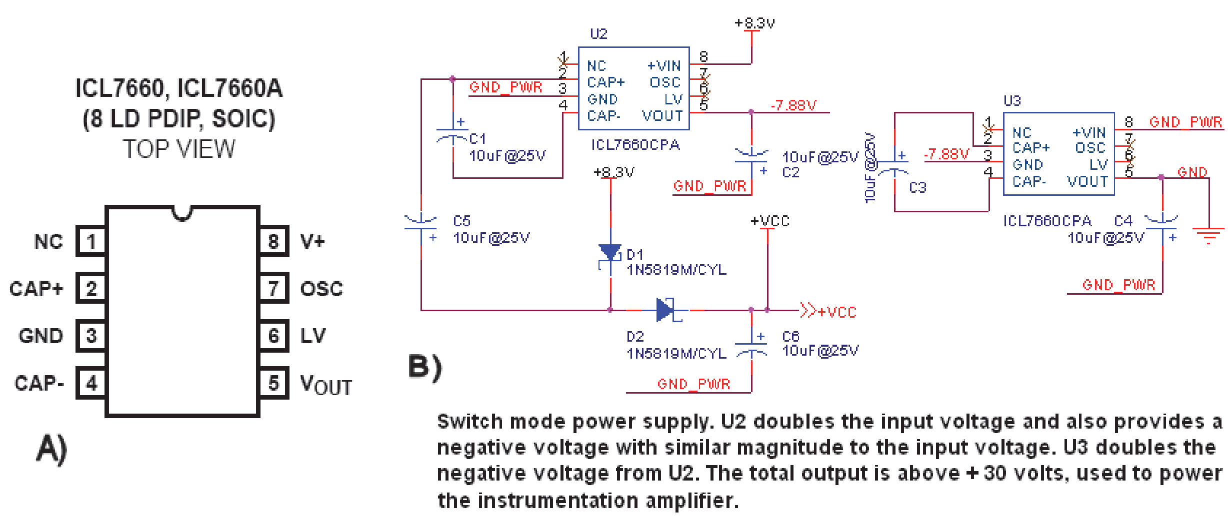


Fig. 7. A) Pinout of the ICL7660 CMOS converter. B) circuit diagram used to increase the TPS7101's output to ~+31V. Reproduced with permission. Copyright 2011 Intersil Americas Inc. All Rights Reserved

Typical current consumption values for the ICL 7660 are 80 µA (ICL7660A) which makes it suitable for this and other battery powered applications. In order to maintain the high efficiency of the CMOS voltage converters it is necessary to reduce the current consumption; therefore the analogue instrumentation must also be a low-power circuit.

2.3 Pressure transducer

The water reservoir is built using an 80 – 100 cm perspex pipe with rubber stoppers on each end. The pressure at the bottom, when the container is full (100 cm H_2O @ 4°C) is 9.806 kPa. Therefore, it is necessary to use a differential pressure transducer with 10 kPa measurement range (Fig. 8).

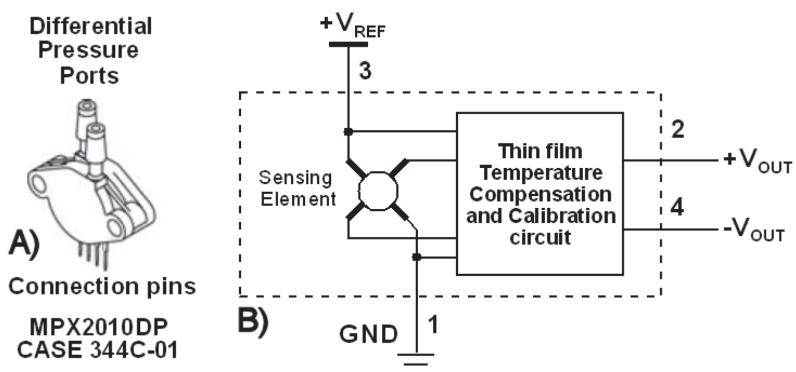


Fig. 8. MPX2010 DP differential pressure transducer A) physical model and B) connections. Reproduced with permission. Copyright Freescale Semiconductor, Inc. 2004 - 2011. All Rights Reserved.

The MPX2010DP differential pressure transducer from Freescale Semiconductor© is a temperature-compensated piezoresistive pressure sensor which provides a very accurate and linear output voltage proportional to the applied pressure in the range of 0 – 10 kPa. The recommended voltage supply is 10V, and the error and linearity figures are specified for 10V. However, the MPX2010DP is a ratiometric device; that is the maximum output voltage depends on the reference voltage which means that a different supply may be used so long as the reference voltage is very stable.

2.3.1 Pressure sensor reference voltage

Recalling that the MPX201DP pressure transducer is a ratiometric device, it is necessary to provide a highly-stable voltage reference signal to achieve correct operation, regardless of voltage and temperature variations.

It is common to find circuits that suggest the use of the voltage supply line to power up the pressure transducer (Fig. 9A). Unless the pressure transducer includes an internal voltage reference supply (i. e. it is a voltage compensated device), it is necessary to use a dedicated voltage reference circuit. (Fig. 9B). In terms of temperature variations, voltage reference circuits are specified in ppm/°C (parts per million per degree centigrade). Consider a reference circuit specified to change at a rate of 100ppm/°C. If the circuit output value is 10V @ 20 °C, exposing the integrated circuit to a 50 °C would change the output from 10V to 10.03 Volts ensuring the correct operation of the transducer. Some devices may also be specified to 10ppm/°C increasing the stability of the overall instrumentation circuit.

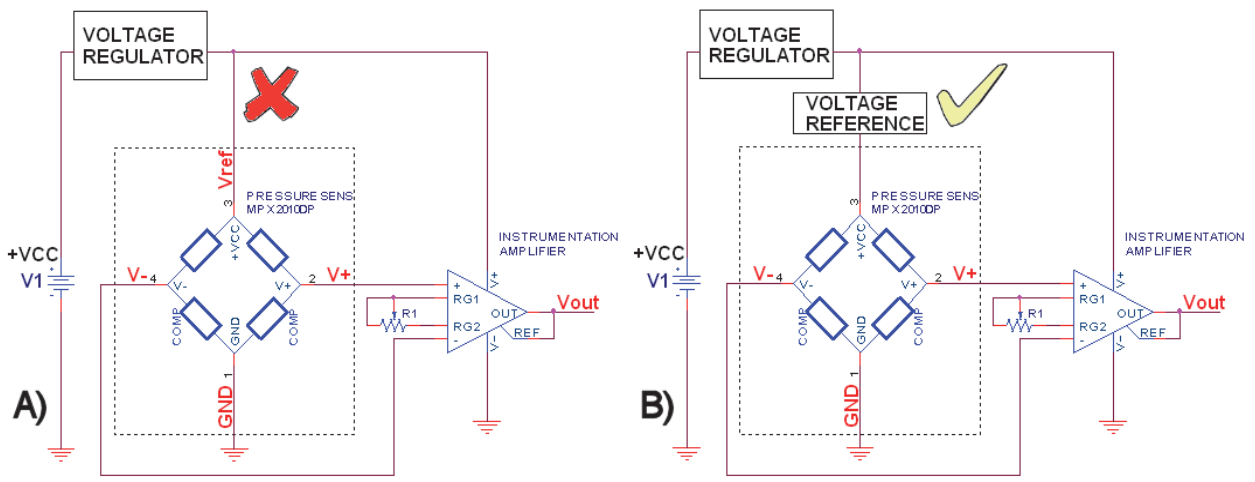


Fig. 9. A) Incorrect voltage supply for a bridge-type sensor. B) The correct use of bridge-type sensor involves the use of a reference voltage circuit.

2.4 Instrumentation amplifier

Instrumentation amplifiers are a type of differential amplifier with high input impedance and adjustable gain that constitute essential building blocks in analogue electronics. One of the classical configurations of instrumentation amplifiers uses three operational amplifiers to form a two-stage amplifying circuit (Figure 10).

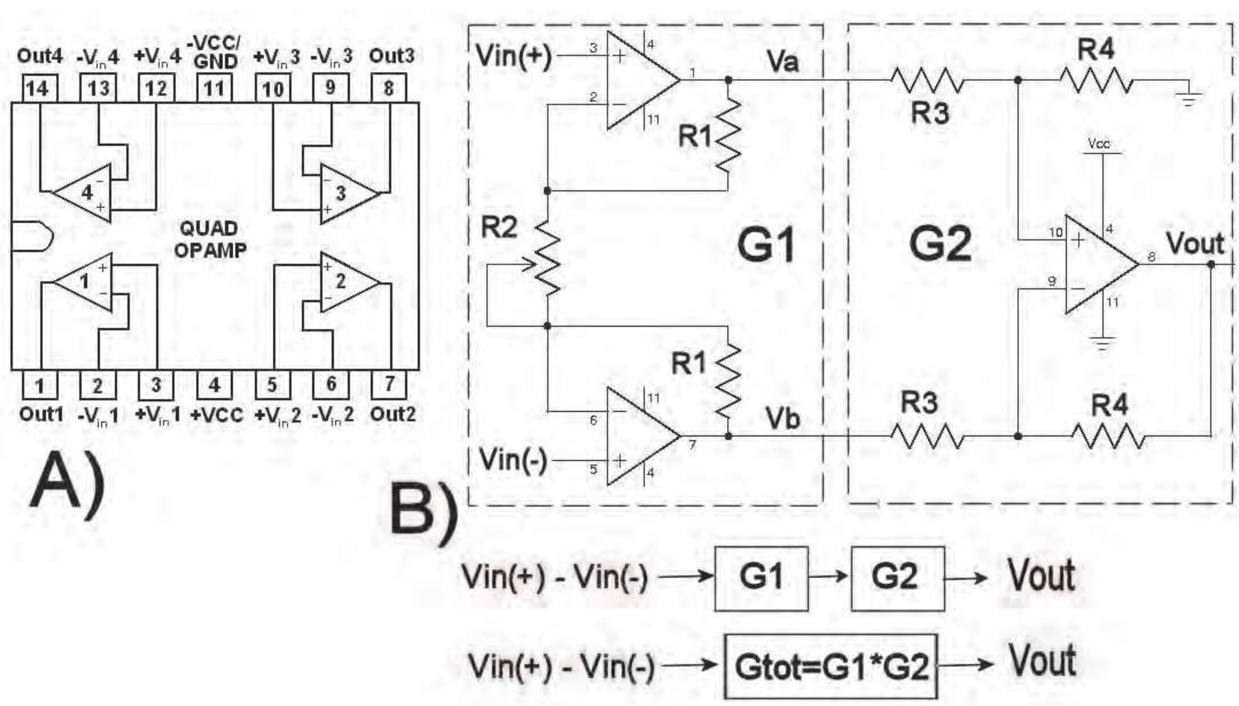


Fig. 10. A) A commercially available quad op-amp can be used to build B) a general-purpose instrumentation amplifier.

The differential input signal feeds the first amplifying stage formed by op-amp 1 and op-amp 2. The output between both op-amp 1 and op-amp 2 (Va and Vb respectively) is differential weighted version of the input voltage. The gain of stage one, G1 (1):

$$G1 = 1 + \frac{2R1}{R2} \quad (1)$$

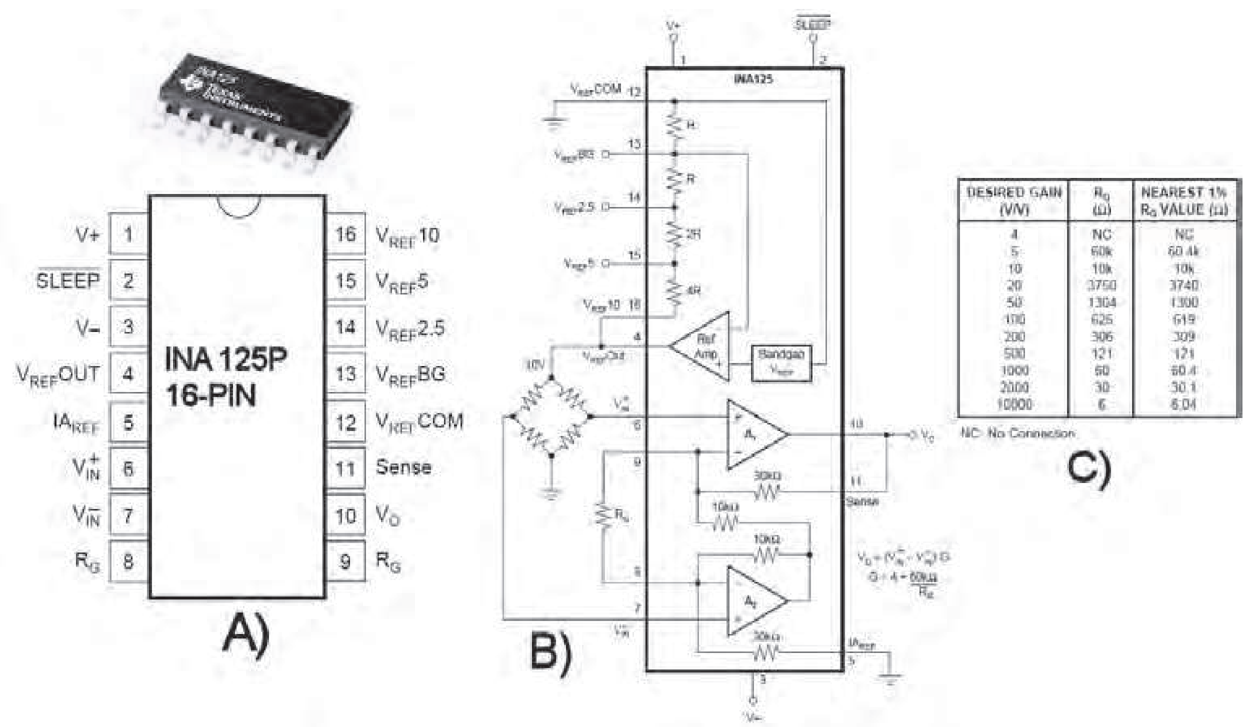
can be adjusted using a single trimming potentiometer, R2. The differential output from stage one, enters a third operational amplifier (op-amp 3) configured as subtracting amplifier with gain, G2, (2):

$$G2 = \frac{R4}{R3} \quad (2)$$

The overall output is then a single-ended version of the differential input voltage. The overall gain of the instrumentation amplifier circuit is the multiplication of both amplifying stages given by (3):

$$G_{TOTAL} = G1\,G2 = \left(1 + \frac{2R1}{R2}\right)\left(\frac{R4}{R3}\right) \quad (3)$$

The importance and usefulness of instrumentation amplifiers have resulted in multiple versatile commercial integrated circuits, with impressive operating characteristics, that allow gain adjustment using a single variable resistor and/or digital signals. One particular integrated circuit that is suitable for portable applications is the INA125 from Texas Instruments© (Fig. 11).



DESIRED GAIN (V/V)	R_G (Ω)	NEAREST 1% R_G VALUE (Ω)
4	NC	NC
5	60k	60.4k
10	10k	10k
20	3750	3740
50	1304	1300
100	625	619
200	306	309
500	121	121
1000	60	60.4
2000	30	30.1
10000	6	6.04

Fig. 11. A) Texas Instruments INA125 instrumentation amplifier pinout, B) typical application circuit and C) gain selection table. Copyright © 2009, Texas Instruments Incorporated. All Rights Reserved.

The INA125 also incorporates a selectable voltage reference circuit, which will be used to supply the reference voltage to the pressure transducer (Fig. 12). The INA125 is a low power device (quiescent current 460 μA) and can operate over a wide range of voltages from a single power supply (2.7V to 36V) or dual supply (±1.35V to ±18V), which makes it suitable for battery powered applications.

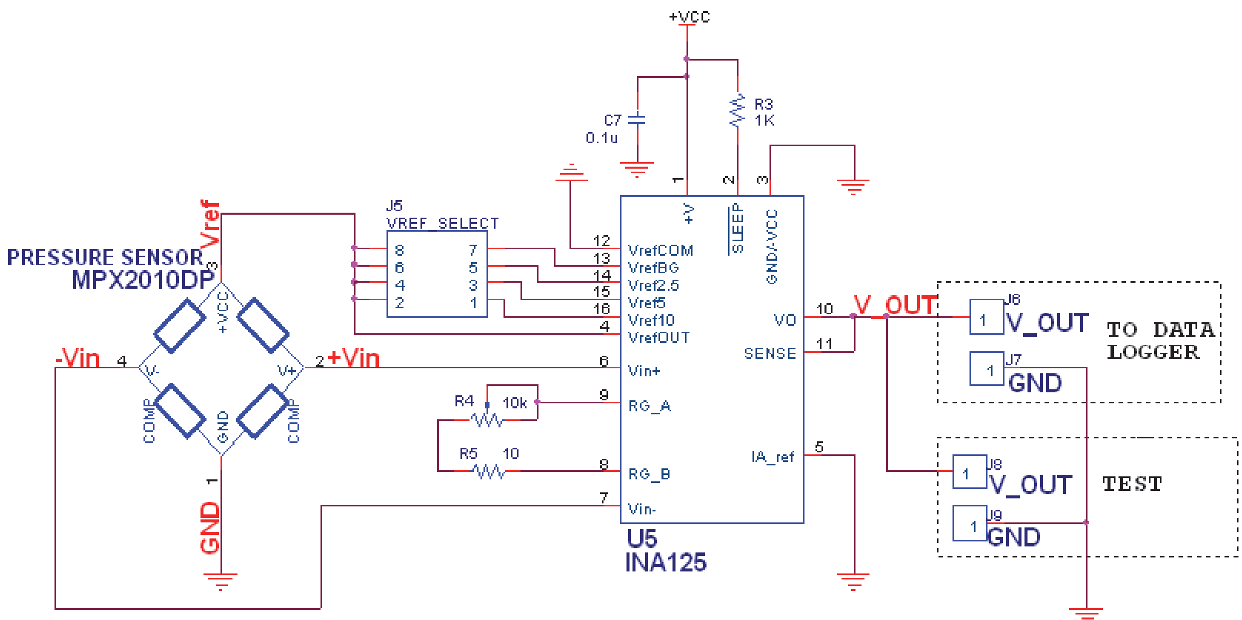


Fig. 12. Circuit diagram of the instrumentation amplifier and voltage reference circuit for the pressure sensor.

The voltage reference value can be adjusted using the jumper J5, to provide 10V, 5V, 2.5 V or 1.24V.

2.5 Complete instrumentation circuit

The complete circuit is shown in Figure 13.

The design includes an on-off switch and connectors to calibrate and monitor the output voltage using a multimeter.

2.6 Ring and reservoir

The size of both the reservoir and the ring may differ depending on the type of soil to be analysed. In addition, the hydraulic conductivity properties of soil vary throughout the test field, and thus a large metallic ring may be used to investigate a large area as much as possible. Analysis of sandy soils may require a larger reservoir compared to clay type soils, because coarse materials have higher hydraulic conductivity and require a larger amount of water to reach the saturated steady state, compared to fine particle soils. In laboratory test trials, it is of little concern the handling of a large reservoir, a heavy metallic ring, computers and electronics instrumentation, and there is tap water available nearby. However, carrying all the necessary materials in field tests may be a difficult task. Therefore the size of the reservoir and metallic ring is a compromise. The infiltrometer described here uses a 1 metre long, 6.35 cm diameter perpex pipe; the ring is made of an iron pipe (8.0 cm long and 8.8 cm diameter) .

2.7 Infiltrometer assembly

Fig. 14 shows the infiltrometer design and assembly, including instrumentation circuitry.

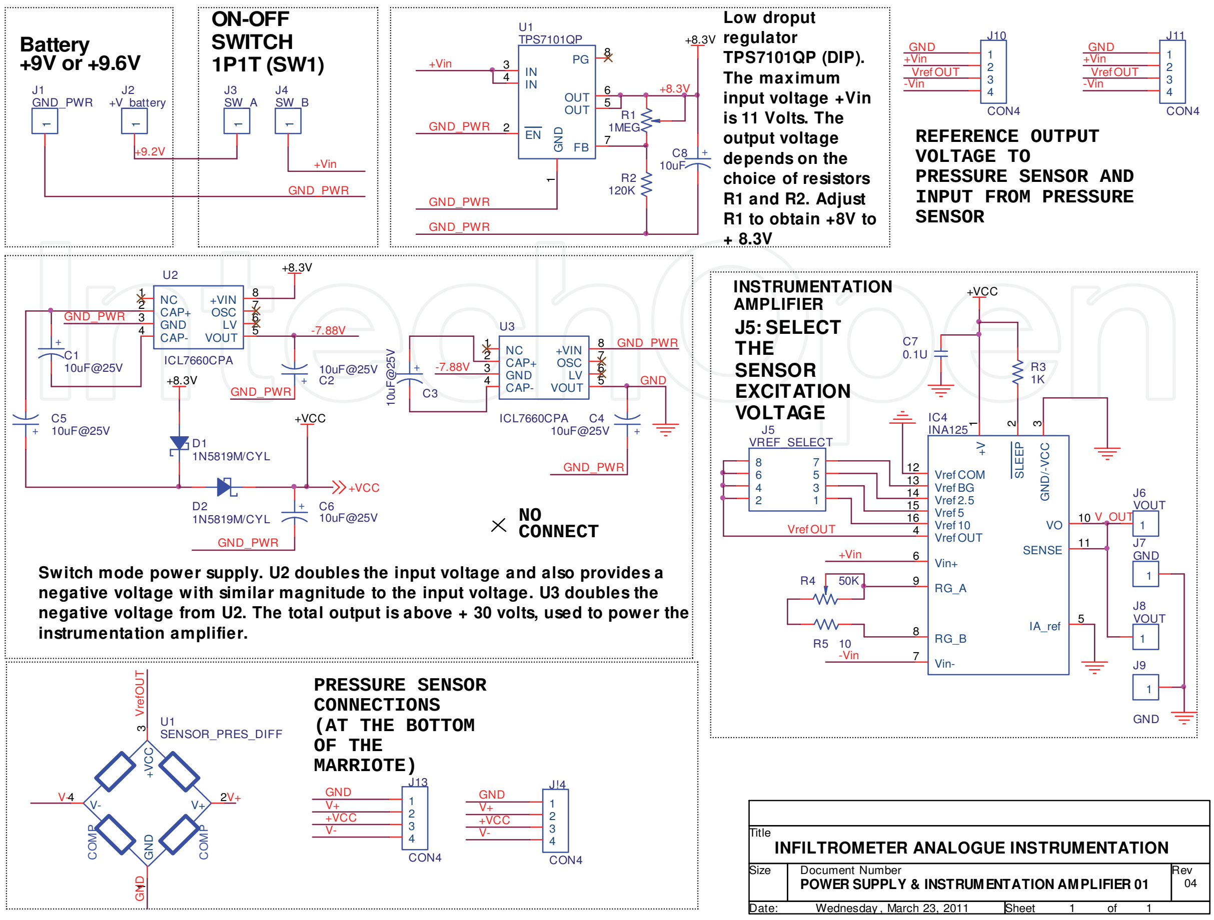


Fig. 13. Instrumentation circuit for measuring infiltration data using a pressure transducer.

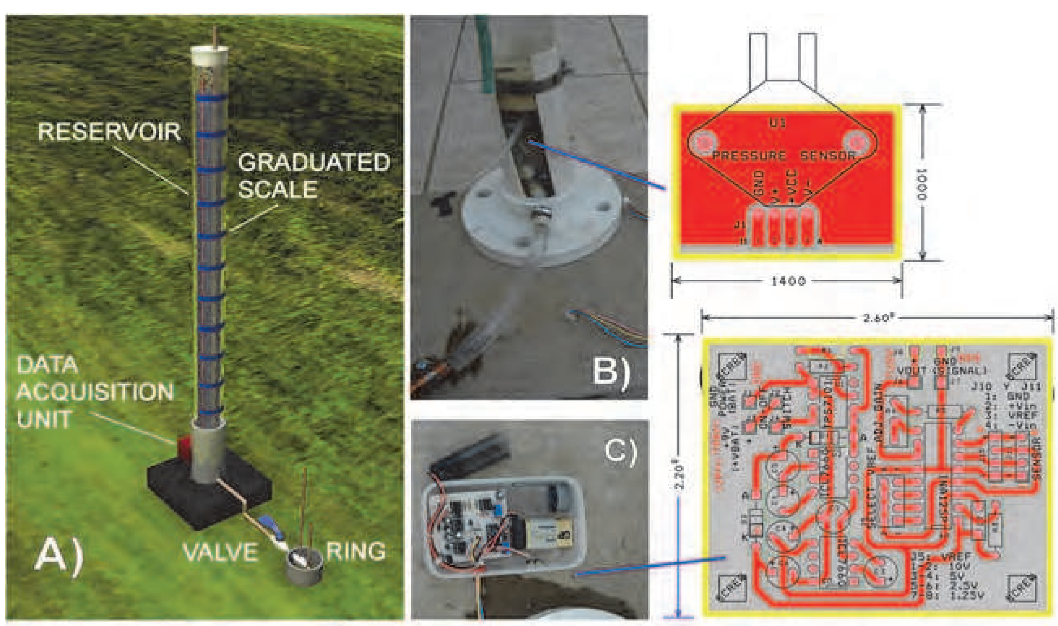


Fig. 14. A) Designed infiltrometer. B) close-up of the pressure sensor assembly. C) The single- sided circuit is fitted into a small (2.6" X 2.2") printed circuit board fits into the plastic enclosure.

The pressure sensor is installed at the bottom of the reservoir and soldered into a small printed circuit board to ensure the correct connectivity between the sensor and the instrumentation circuitry. The instrumentation circuit is installed, outside the infiltrometer, inside a small plastic enclosure, as well as the battery and data logger. Once the plastic enclosure is attached to the infiltrometer, the data logger can be removed from the electronics without removing any connections. The result is a compact versatile infiltrometer, which can easily be transported for field tests.

2.8 Test results

The infiltrometer was tested in two different test locations around the Cuitzeo Lake watershed (19º58' N, 101º08' W): sandy loam (Fig. 15A) and sandy soil (Fig. 15B).

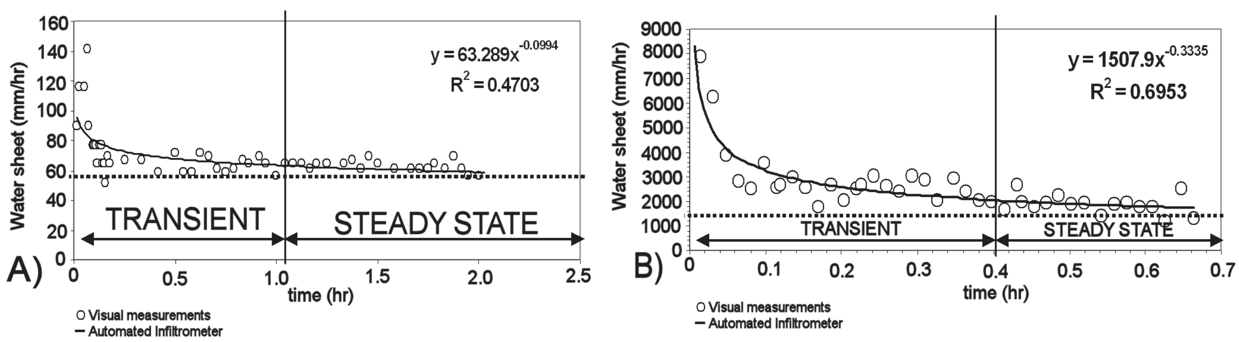


Fig. 15. Comparison of test results using the automated infiltrometer vs visual measurements for A) sandy loam and B) sandy soils.

The results from the automated measurement data acquisition system are much more consistent throughout the test, improving the quality of information compared to visual observations. Table 2 shows a summary of hydraulic conductivity results, using the Wu2 method and data from the steady state region.

Type of Soil	Measurement Method	Average Hydraulic conductivity K_{Fs} (mm/hr)	Standard Deviation	Number of test trials N
Sandy loam	Automated infiltrometer	49.65	21.72	7
	Visual Observations	68.31	42.85	7
Sandy soil	Automated infiltrometer	2282.2	429.98	5
	Visual Observations	1671.82	793.56	5

Table 2. Summary of the hydraulic conductivity results obtained from automated measurements and visual observations.

The automated infiltrometer can produce more reliable information than that obtained using visual measurements. For instance the standard deviation obtained from automatic data is smaller compared to visual observation. The resolution for a 1 metre water column is 1.66 mm approximately. The equipment presented in this case study is considerably easy to implement, low cost and can be used for laboratory and field test trials alike. Nevertheless, it still relies on the use of commercial data loggers. Alternatively, a dedicated data logger based on an ultra-low power microcontroller can be used to allow reviewing the data on-site and also to store the results of multiple test trials.

3. Case study 2: Automated infiltrometer using a dedicated data logger

Using a commercial data logger and relatively simple analogue electronics allows rapid development of test prototypes. On the other hand, since the determination of hydraulic conductivity infiltration requires performing multiple tests, it is desirable that all the results are stored in non-volatile memory without having to transfer the results to the host PC, immediately after each test has been concluded. Higher resolution may also be required for correct in-situ characterization of different types of soils. Moreover, since measurements are not taken continuously (i. e. the lowest sampling rate may be 1 second) it may be desirable to be able to shutdown the analogue circuitry in between measurements to extend battery life. Fig. 16 shows the schematic diagram of the proposed data acquisition system.

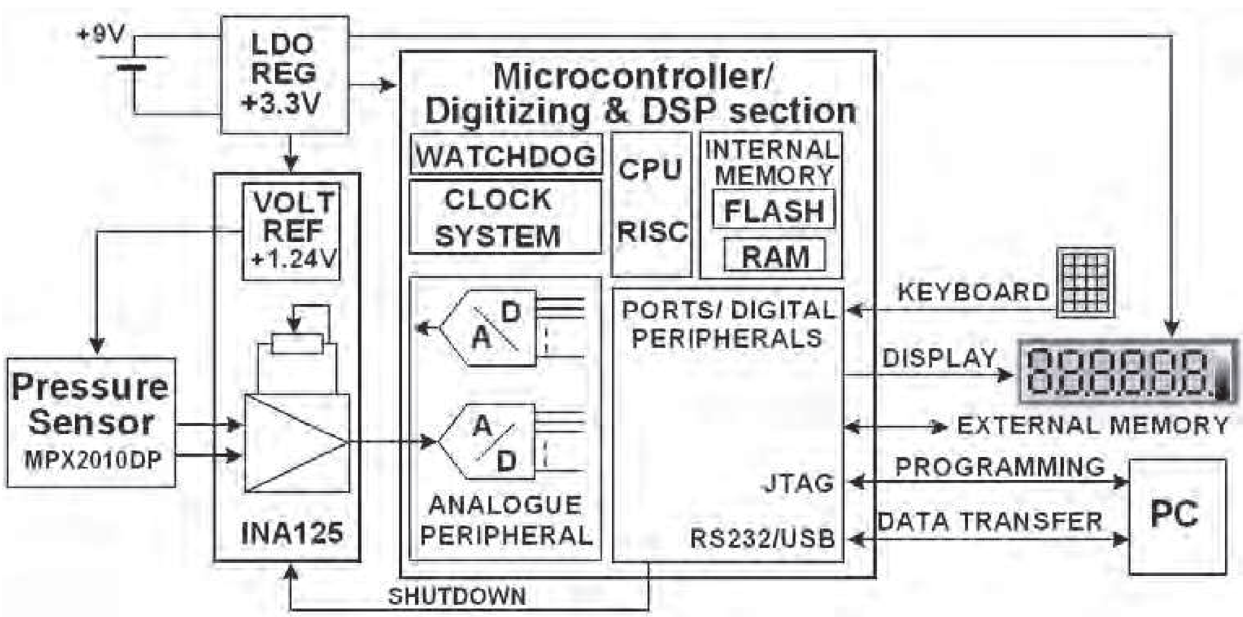


Fig. 16. Schematic diagram of a data acquisition system based on a low power microcontroller, specially designed for hydraulic infiltration measurements.

3.1 Dedicate data logger operation description

The equipment follows the same design philosophy for case study 1. The measurement system is based on the MPX2010DP pressure sensor, and the INA125 instrumentation amplifier is used to provide the reference voltage and measure the differential output from the transducer. However, the digitizing section is now based on a microcontroller.

3.1.1 Choosing the microcontroller

Several powerful microcontrollers are available from multiple companies that can be used to perform all the necessary data acquisition and signal processing operations. One particularly useful family of powerful microcontrollers suitable for low power operation is the MSP430 series from Texas Instruments© (Fig. 17). Case study 2 is based on MSP430F149IPAG microcontroller from Texas Instruments©. The MSP430 is a 16-bit RISC, ultra-low-power device with five power-saving modes, two built-in 16-bit timers, a fast 12-bit A/D converter, two universal serial synchronous/asynchronous communication interfaces (USART), 48 Input/Output pins, 60 kB of flash memory and 2 kB of RAM, which permits the implementation of all the functions required to build the data acquisition system. Initially, it was considered that basic signal processing algorithms (digital filter) are the main functions to be included. However, a JTAG interface implemented on the prototype allows in-system programming so that the equipment can be updated, and further signal processing algorithms can be included in the future, without changing the hardware.

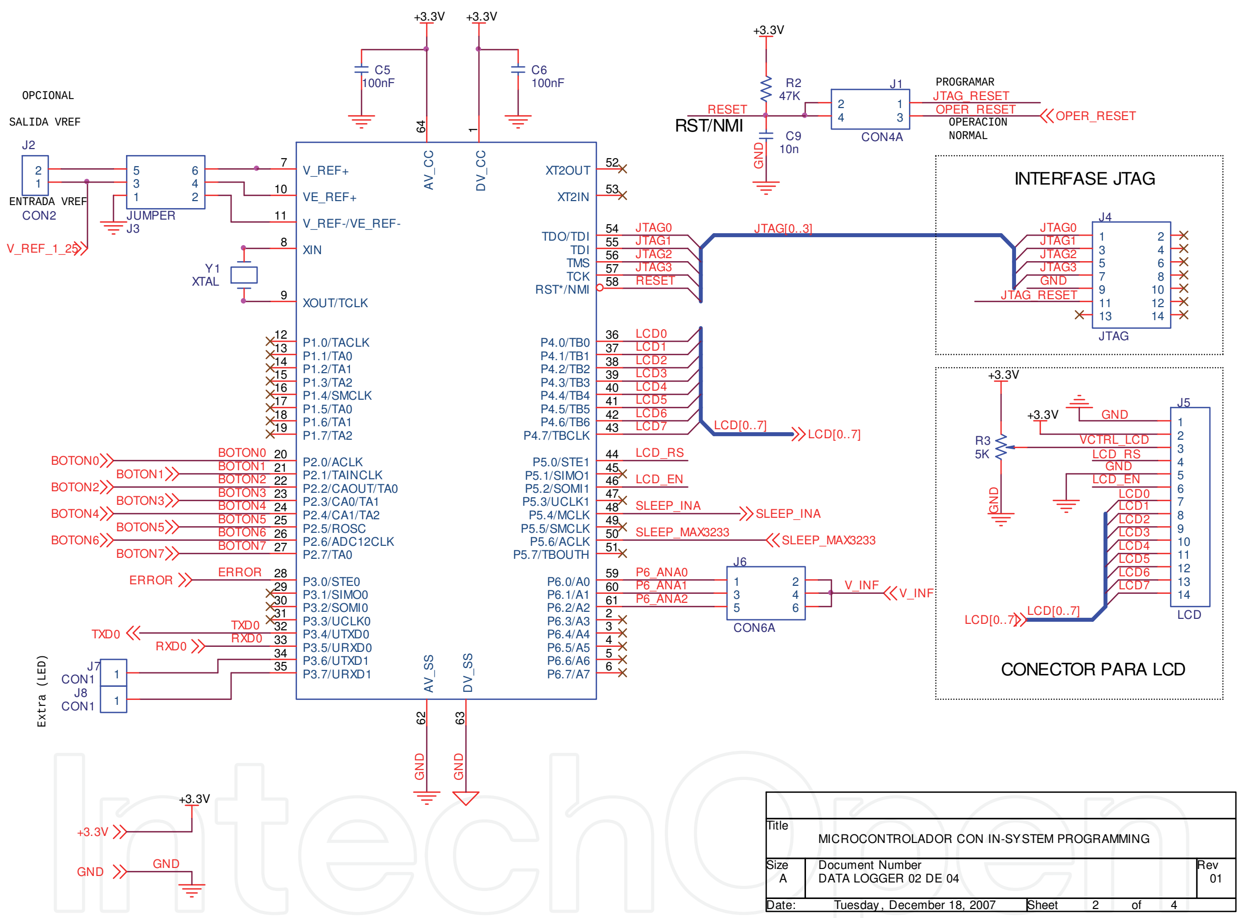


Fig. 17. Schematic diagram of the data logger based on the MSP430F148IPAG.

3.2 Operation of the data logger

The microcontroller interfaces with the user through a keyboard and LCD display, thus allowing the operation of the device in test fields, and reviewing the measured information in real time or right after the test has concluded. The microcontroller controls the data acquisition process, and stores each measurement in non-volatile flash memory. The microcontroller shuts down the analogue circuit in between samples to save battery power and enters a low-power mode. Prior to taking each sample, the microcontroller turns on the analogue circuit and waits 100 ms to allow the analogue output to settle and take a stable measurement. The data logger unit uses a 9V battery but it can also operate with a supply voltage as low as 4V. The MSP430 itself operates with 3.3V, so the same voltage is used throughout the circuit. The INA125 is very useful in this case, because it can operate with a voltage as low as 2.7V. The INA125's internal reference voltage circuitry requires that the power supply voltage is, at least, 1.25 V above the desired reference voltage and thus only the +1.24 V reference option can be used. The MSP430 internal voltage reference is adjusted to 2.5 volts, and the INA125 is adjusted to output 2.5V when the water column is full. In addition to accuracy, versatility, and compactness, it is necessary that the equipment can operate in low power mode to increase battery life. Therefore the MSP430 records data at fixed, programmable intervals, from 1 second, and then 10 seconds steps up to 60 minutes, selected by the user prior to each test. A real-time clock algorithm is implemented, using Timer A, so that the microcontroller can enter energy saving mode LMP3 consuming 2μA approximately in between samples. During the energy saving mode, the microcontroller also turns off the transducer voltage reference source, instrumentation amplifier and display. 100 miliseconds before each measurement is taken, the voltage reference source and instrumentation amplifier are activated, allowing the measurement to settle. The user can select the LCD to remain off while taking measurements. During operation, the LCD can also be activated temporarily to supervise the measured data, and then switched off again. The results of each test are stored in the flash memory, starting at memory block 0x3F. Before each test, the microcontroller detects which memory blocks are used and starts saving data in the next empty block. Thus, up to 90 tests can be conducted in-situ. The user can also select which memory block to erase, (i.e. which experiment) instead of erasing the entire memory, also contributing to saving battery life.

3.3 Electronics instrumentation assembly

Fig. 18A shows the double-sided printed circuit board. The board, keyboard and display and battery are fitted into a plastic enclosure (Fig 18B, 18C). In a similar manner to case study one, the pressure transducer is located below the reservoir and the wires carrying the voltage supply and signals are connected to the data logger.

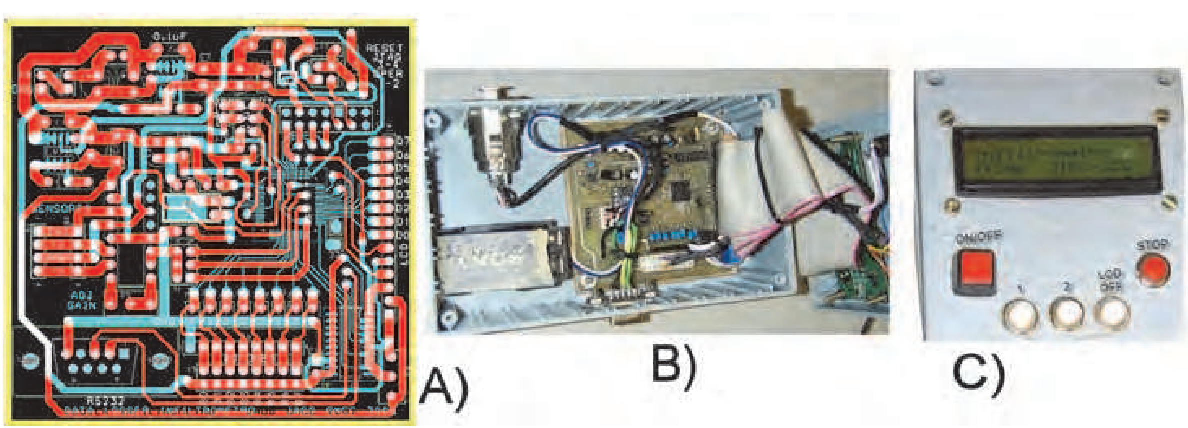


Fig. 18. A) Data Logger Printed Circuit Board (PCB). B) The PCB, C) keyboard and display and interface connections are also fitted in the plastic enclosure.

3.4 Transferring data for permanent storage and analysis

A C++ program interface was implemented to allow the user to transfer the data to a host PC for permanent storage, off-line results visualization and analysis (Fig. 19). Prior to each test the user can set the time, date and sampling rate for the experiment. The test information is stored at the beginning of each memory block, followed by the column height measurements. Once the experiment (or several experiments) has been completed, the user can review the measured data in-situ. Alternatively the user can transfer the results to a host PC, through the RS232 connection or with RS232-USB adaptors, to allow compatibility with current PC configuration ports.

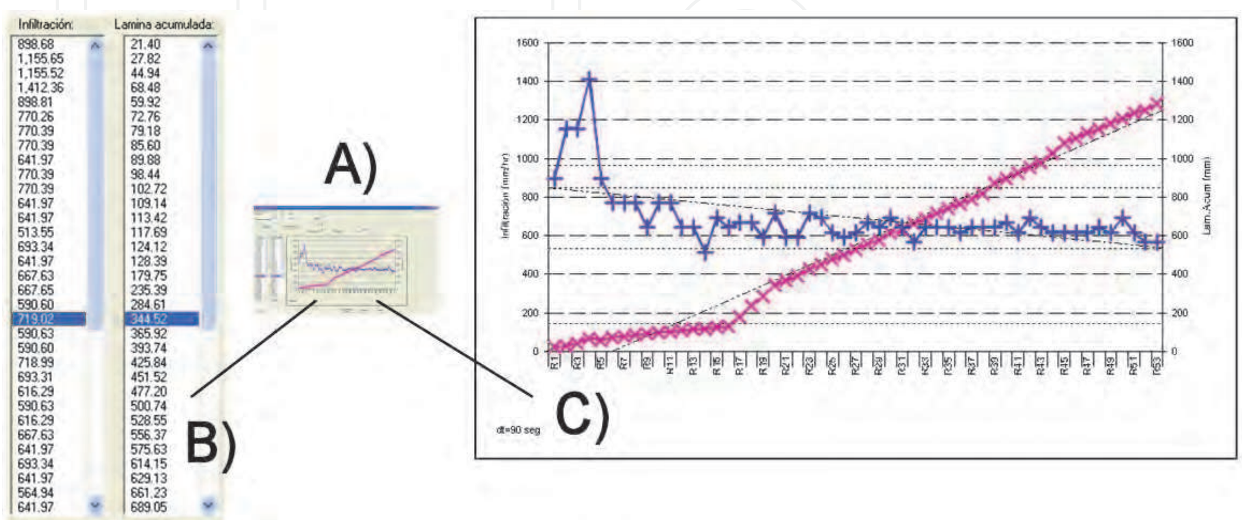


Fig. 19. A) The C++ software B) analyses the measurements using the Wu1 and Wu2 methods and C) plots the results.

The software processes the data and allows inspection of each value (Figure 18B). The program calculates hydraulic conductivity using the WU1 and WU2 methods, thus allowing result comparison.

3.5 Test results

The infiltrometer was tested in three different test locations around the Cuitzeo Lake watershed (19º58' N, 101º08' W): clay, loam and sand (Table 3).

Site		Wu1	Wu2	Guelph
Clay	Average Kfs	5.497	2.231	2.782
	Standard deviation	8.163	3.185	2.584
	Number of test trials, N	26	26	13
Loam	Average Kfs	79.551	150.401	95
	Standard deviation	63.58	82.86	97.05
	Number of test trials, N	36	36	3
Sand	Average Kfs	708.30	963.41	----
	Standard deviation	722.37	758.28	----
	Number of test trials, N	9	11	-----

Table 3. Summary of hydraulic conductivity tests using the automated infiltrometer.

Measurements where also obtained with a Guelph permeamenter, for comparison, except for sandy soil, because it was not possible to reach the required depth to introduce the 50 x

120 mm probe due to sample collapse. A commercial Guelph permeameter is a constant-head device, which also operates on the Mariotte siphon principle and allows simultaneous measurement of field saturated hydraulic conductivity, matric flux potential, and soil sorptivity in the field (Soilmoisture Equipment Corporation, Santa Barbara California, U. S.). In this work the Guelph permeameter operates as a "benchmark methodology" and is not to be considered it as the only valid acceptable method. Direct point-by-point comparison of results using different test methods is not valid since data is taken from different locations. In addition, the automated infiltrometer presented is limited to conduct tests at the surface, so Kfs variations at other soil depths is out of reach, in contrast with the Guelph permeameter, capable of measuring Kfs up to 80 cm depth without any special instruments. Nevertheless, the device described in this case study allowed the estimation of field saturated hydraulic conductivity in agreement with the Guelph permeameter in some cases.

4. Conclusion

The automated infiltrometers presented in this work, can produce reliable information about the infiltration process in-situ, with little supervision. The devices also allow the acquisition of a large number of measurements compared to visually obtained information, thus facilitating the calculation of Ks. Case study one shows the use of low-cost data loggers to automate the measurement process. A considerable simple instrumentation circuit is necessary to obtain the maximum resolution from the data logger. If a dedicated device is required, case study 2 shows the use of microcontroller technology to build the data logger unit. The DAQ units allow sample time adjustment on-site, which permits the investigation of different types of soils. The automated infiltrometer offers a ~0.25mm column height measurement resolution improving the quality of Ks calculations. Both cases present affordable and reliable instrumentation solutions, that can be built for about $ 100 US dollars without considering development time investment. Current and future work includes the development of a multi-channel simultaneous sampling system, so that the test field can be correctly characterized using multiple infiltrometers located around the test site.

5. Acknowledgment

The authors acknowledge the financial support from Public Education Secretariat–Mexico (Spanish: SEP-Secretaría de Educación Pública) under grants SEP-DGEST 4328.11-P and PROMEP ITMOR-CA1 103.5/11/1091 to carry out this work.

6. References

Amézketa Lizarraga, E.; Aragüés Lafarga, R. & Gazol Lostao R. (2002). Desarrollo de un infiltrómetro automático y su aplicación en campo. *Investigación agraria. Producción y protección vegetales*, Vol. 17, pp. 131-142, ISSN 0213-5000

Angulo-Jaramillo, R.; Vandervaere, J. P.; Roulier, S.; Thony, J. L.; Gaudet, J. P. & Vauclin M. (2000). Field measurement of soil surface hydraulic properties by disc and ring infiltrometers: A review and recent developments, *Soil and Tillage Research*, Vol. 55, pp. 1-29, ISSN 0167-1987

Ankeny, M. D.; Kaspar, T. C. & Horton. R. (1988). Design for an Automated Tension Infiltrometer. *Soil Sci. Soc. Am., J.,* Vol. 52, pp. 893-896, ISSN 0361-5995

Ankeny, M. D. (1992). Methods and Theory for Unconfined Infiltration Measurements. In G. C. Topp, W. D. Reynolds, and R. E. Green, (Eds). Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice. *Soil Science Society of America, Inc.* pp. 123-141

Bodhinayake, W.; Si, B. C. & Noborio, K. (2004). Determination of Hydraulic Properties in Sloping Landscapes from Tension and Double-Ring Infiltrometers, *Vadose Zone J.* Vol 3, pp. 964-970, ISSN 1539-1663

Bull A. D. (1949). Automatic Recording Infiltrometer, US Patent 2,540,096, 1949

Carlón-Allende, T. (2006). Regionalización hidrológica en la cuenca del lago de Cuitzeo. MSc thesis. Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México.

Casey, F. X. M. & Derby, N. E. (2002). Improved design for an automated tension infiltrometer, *Soil Sci. Soc. Am. J.*, Vol. 66, pp. 64-67, ISSN 0361-5995

Chunye, L.; Greenwald, D. & Banin, A. (2003). Temperature Dependence of Infiltration Rate during Large Scale Water Recharge into Soils, *Soil Sci. Soc. Am. J.*, Vol. 67, pp. 487–493, ISSN 0361-5995

CONAGUA. Mexican National Water Comission (Comisión Nacional del Agua) (2008). *Programa Nacional Hídrico 2007-2012,* ISBN 968-817-836-5, México, D. F., Mexico.

CONAGUA. Mexican National Water Comission (Comisión Nacional del Agua) (2010). *Estadísticas Agrícolas de los Distritos de Riego. Año agrícola 2008-2009,* Available from http://www.conagua.gob.mx, Last date visited: February 1st, 2011.

Constanz, J., & Murphy. F. (1987). An automated technique for flow measurement from Mariotte reservoirs. *Soil Sci. Soc. Am. J.*, Vol. 51, pp. 252-254, ISSN 0361-5995

Das Gupta, S.; Mohanty, B. P. & Köhne, J. M. (2006). Soil Hydraulic Conductivities and their Spatial and Temporal Variations in a Vertisol, *Soil Sci. Soc. Am. J.,* Vol. 70, pp. 1872-1881, ISSN 0361-5995

Dudley, L. M.; Bialkowski, S.; Or, D. & Junkermeier, C. (2003). Low Frequency Impedance Behavior of Montmorillonite Suspensions: Polarization Mechanisms in the Low Frequency Domain, *Soil Sci. Soc. Am. J.,* Vol. 67, pp. 518–526. ISSN 0361-5995

Esteves, M.; Descroix, L.; Mathys, N. & Lapetite. J. M. (2005). Soil hydraulic properties in a marly gully catchment (Draix, France), *CATENA,* Vol. 63, pp. 282-298. ISSN 0341-8162

Eynard, A.; Schumacher, T. E.; Lindstrom, M. J. & Malo D. D. (2004). Porosity and Pore-Size Distribution in Cultivated Ustolls and Usterts, *Soil Sci. Soc. Am. J.,* Vol. 68, pp. 1927-1934, ISSN 0361-5995

Gimmi, T. & Ursino, N. (2004). Mapping Material Distribution in a heterogeneous Sand Tank by Image Analysis, *Soil Sci. Soc. Am. J.,* Vol. 68, pp. 508–1514, ISSN 0361-5995

Johnson, D. O.; Arriaga, F. J. & Lowery. B. (2005). Automation of a falling head permeameter for rapid determination of hydraulic conductivity of multiple samples, *Soil Sci. Soc. Am. J.,* Vol. 69, pp. 828-833. ISSN 0361-5995

Kluitenberg, G. J. & Warrick, A. W. (2001). Improved Evaluation Procedure For Heat-Pulse Soil Water Flux Density Method. *Soil Sci. Soc. Am. J.,* Vol. 65, pp. 320–323, ISSN 0361-5995.

Mbagwu, J. S. C. (1995). Saturated hydraulic conductivity in relation to physical properties of soils in the Nsukka Plains, southeastern Nigeria, *Geoderma*, Vol, 68, pp. 51-66, ISSN 0016-7061

Overman, A. R.; Peverly, J. H. & Miller. R. J. (1968). Hydraulic conductivity measurements with a pressure transducer, *Soil Sci. Soc. Am. Proc.* Vol. 32, pp. 884-886.

Park, E. J. & Smucker, A. J. M. (2005). Saturated Hydraulic Conductivity and Porosity within Macroaggregates Modified by Tillage, *Soil Sci. Soc. Am. J.,* Vol. 69, pp. 38–45, ISSN 0361-5995.

Pedro Vaz, C. M. & Hopmans, Jan W. (2001). Simultaneous Measurement of Soil Penetration Resistance and Water Content with a Combined Penetrometer–TDR Moisture Probe. *Soil Sci. Soc. Am. J.*, Vol. 65, pp. 4–12, ISSN 0361-5995

Prieksat, M. A.; Ankeny, M. D. & Kaspar, T. C. (1992). Design for an automated, selfregulating, single-ring infiltrometer. *Soil Sci. Soc. Am. J.*, Vol. 56, pp. 1409-1411. ISSN 0361-5995

Prunty, L. & Bell, J. (2005). Soil Temperature Change over Time during Infiltration, *Soil Sci. Soc. Am. J.,* Vol. 69, pp. 766–775, ISSN 0361-5995

Rachman, A.; Anderson, S. H.; Gantzer, C. J. & Alberts, E. E. (2004). Soil Hydraulic Properties Influenced by Stiff-Stemmed Grass Hedge Systems, *Soil Sci. Soc. Am. J.*, Vol. 68, pp. 1386–1393, ISSN 0361-5995.

Reynolds, W. D., y D. Elrick. 1991. Determination of Hydraulic Conductivity Using a Tension Infiltrometer. *Soil Sci. Soc. Am. J.*, Vol. 55, pp. 633-639. ISSN 0361-5995

Schwartz, R, C. & Evett, S. R. (2003). Conjunctive Use of Tension Infiltrometry and Time-Domain Reflectometry for Inverse Estimation of Soil Hydraulic Properties, *Vadose Zone J.*, November 1; Vol. 2, Issue 4, pp. 530 – 538.

Seobi, T.; Anderson, S. H.; Udawatta, R. P. & Gantzer, C. J. (2005). Influence of Grass and Agroforestry Buffer Strips on Soil Hydraulic Properties for an Albaqualf, *Soil Sci. Soc. Am. J.*, Vol. 69, pp. 893–901, ISSN 0361-5995

Seyfried, M. S. & Murdock, M. D. (2004). Measurement of Soil Water Content with a 50-MHz Soil Dielectric Sensor. *Soil Sci. Soc. Am. J.*, Vol. 68, pp. 394–403. ISSN 0361-5995

Simpson, M. J. (2006). Nuclear Magnetic Resonance Based Investigations of Contaminant Interactions with Soil Organic Matter. *Soil Sci. Soc. Am. J.*, Vol. 70, pp. 995–1004, ISSN 0361-5995

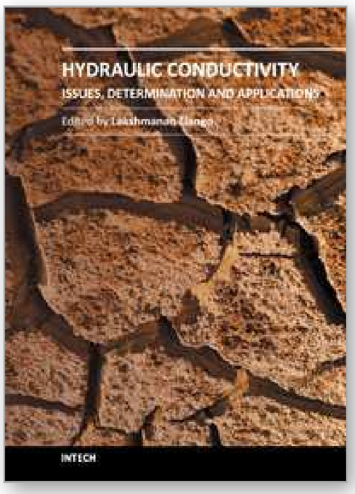
Soracco, G. (2003). *Relación entre la conductividad hidráulica saturada y la densidad aparente en tres situaciones de manejo contrastantes*, in D. Lobo Luján, D. Gabriels, G. Soto, "Evaluación de Parámetros y Procesos Hidrológicos en el Suelo", pp. 35-38, UNESCO, Paris, France.

Špongrová, K. 2006. Design of an automated tension infiltrometer for unsaturated hydraulic conductivity measurement. M.Sc. by Research. Cranfield University.

Wilson, M. A.; Brown, R. J. E.; Hoff, W. D. & Carter, M. A. (2000). A falling head permeameter for the measurement of the hydraulic conductivity of granular solids. Review of Scientific Instruments, Vol. 71, pp. 3942–3946, ISSN 0034-6748.

Wu, L. & Pan, L. (1997). A Generalized Solution to Infiltration from Single-Ring Infiltrometers by Scaling, *Soil Sci. Soc. Am. J.*, Vol. 61, pp. 1318-1322, ISSN 0361-5995

Wu, L.; Pan, L; Mitchell, J. & Sanden, B. (1999). Measuring Saturated Hydraulic Conductivity using a Generalized Solution for Single-Ring Infiltrometers, *Soil Sci. Soc. Am. J.,* Vol. 63, pp. 788-792, ISSN 0361-5995



Hydraulic Conductivity - Issues, Determination and Applications
Edited by Prof. Lakshmanan Elango

ISBN 978-953-307-288-3
Hard cover, 434 pages
Publisher InTech
Published online 23, November, 2011
Published in print edition November, 2011

There are several books on broad aspects of hydrogeology, groundwater hydrology and geohydrology, which do not discuss in detail on the intrigues of hydraulic conductivity elaborately. However, this book on Hydraulic Conductivity presents comprehensive reviews of new measurements and numerical techniques for estimating hydraulic conductivity. This is achieved by the chapters written by various experts in this field of research into a number of clustered themes covering different aspects of hydraulic conductivity. The sections in the book are: Hydraulic conductivity and its importance, Hydraulic conductivity and plant systems, Determination by mathematical and laboratory methods, Determination by field techniques and Modelling and hydraulic conductivity. Each of these sections of the book includes chapters highlighting the salient aspects and most of these chapters explain the facts with the help of some case studies. Thus this book has a good mix of chapters dealing with various and vital aspects of hydraulic conductivity from various authors of different countries.