IRRIGATION AND DRAINAGE
Irrig. and Drain. **59**: 524–534 (2010)
Published online 7 May 2009 in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ird.511

AIRBORNE REMOTE SENSING FOR DETECTION OF IRRIGATION CANAL LEAKAGE[†,‡]

YANBO HUANG[1]*, GUY FIPPS[2], STEPHAN J. MAAS[3] AND REGINALD S. FLETCHER[4]

[1]*Agricultural Research Service, United States Department of Agriculture, Stoneville, Mississippi, USA*
[2]*Department of Biological and Agricultural Engineering, Texas A&M University, College Station, Texas, USA*
[3]*Department of Plant and Soil Science, Texas Tech University, Lubbock, Texas, USA*
[4]*Agricultural Research Service, United States Department of Agriculture, Weslaco, Texas, USA*

ABSTRACT

Traditional field survey methods for detection of water leaks in irrigation canal systems are costly and time-consuming. In this study, a rapid, cost-effective method was developed for identifying irrigation canal locations likely to have leaks and/or seepage. The method involves the use of a multispectral imager equipped with red, near infrared, and thermal sensors which is mounted on an aircraft and flown at low altitude to collect the images. A three-step process, image acquisition, image processing, and field reconnaissance, was developed for processing the imagery and identification of locations likely to have leaks. The method was evaluated in the Lower Rio Grande Valley of Texas, USA. Images were collected of 24 selected canal segments within 11 irrigation districts in this region. Evaluation of the imagery indicated that 140 sites had possible canal leakage problems (point leak and/or seepage). A field site evaluation form was developed and used to document the type and severity of the leaks at 28 of the sites. Twenty-six sites were confirmed to have leaks, representing a success rate of 93%. The methods used in this study should have widespread application for detecting leaks and seepage in irrigation canals. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: water leak detection; airborne remote sensing; multispectral imaging; irrigation distribution network; canal leakage; field reconnaissance; thermal imagery; normalized difference vegetation index

Received 1 May 2008; Revised 3 February 2009; Accepted 4 February 2009

RÉSUMÉ

Les méthodes d'enquête sur le terrain pour la détection de fuites d'eau dans les systèmes de canaux d'irrigation sont coûteuses et prennent du temps. Dans cette étude, une méthode rapide et efficace a été développée pour identifier les endroits des canaux d'irrigation susceptibles d'avoir des fuites et/ou des infiltrations. La méthode implique l'utilisation d'un imageur multispectral équipé de capteurs thermiques, rouge et proche infrarouge monté sur un avion volant à basse altitude pour recueillir les images. Un processus en trois étapes – acquisition d'image, traitement d'image et reconnaissance de terrain – a été développé pour le traitement des images et l'identification des sites susceptibles d'avoir des fuites. La méthode a été évaluée dans le Lower Rio Grande Valley, Texas, USA. Les images de 24 segments de canaux d'irrigation ont été recueillies dans les 11 districts de cette région. L'évaluation des images a indiqué que 140 sites ont de possibles problèmes de fuite (point de fuite et/ou d'infiltration). Un formulaire d'évaluation du site a été développé et utilisé pour documenter le type et la gravité de la fuite pour 28 de ces sites. Les fuites ont été confirmées sur 26 sites, ce qui représente un taux de réussite de 93%.

* Correspondence to: Yanbo Huang, 141 Experiment Station Rd. USDA-ARS, JWDSRC, APTRU, Stoneville, MS 38776, USA.
E-mail: Yanbo.Huang@ars.usda.gov

[†]Télédétection aéroportée pour la détection des fuites de canal d'irrigation.
[‡]The contributions of Y. Huang and R. S. Fletcher to this article were prepared as part of their duties as a United States Federal Government employee.

Les méthodes utilisées dans cette étude devraient avoir une application généralisée de détection des fuites et des infiltrations dans les canaux d'irrigation.

MOTS CLÉS: détection de fuites d'eau; télédétection aéroportée; imagerie multispectrale; réseau d'irrigation; canal de fuite; reconnaissance de terrain; imagerie thermique; indice normalisé de différence de végétation

INTRODUCTION

This paper reports on the research of developing a method that applies airborne multispectral remote sensing techniques for determining the leaks in irrigation canals in a timely and cost-effective way. This method employs visible, near infrared (NIR), and thermal imaging to overcome the limitation from relying on an individual imaging sensor.

The study area is the Lower Rio Grande Valley (LRGV), a four-county area located at the southern tip of Texas along the Mexican border (Figure 1). In the LRGV, irrigation districts deliver raw water to municipal treatment plants through the same canals and underground pipelines used to deliver water to farms through about 4830 km (3000 miles) of canals, pipelines, and Resacas, former channels of the Rio Grande found in the southern half of Cameron County. In 2000, the total water supply for this region was 1.56×10^9 m^3 (1 278 090 ac-ft) (Texas Water Development Board (TWDB), 2002). Fipps (2000) estimated that the irrigation districts had an average conveyance efficiency of 70%, resulting in average annual water losses from the distribution networks of 4.55×10^8 m^3 (373

Figure 1. GIS map of the Lower Rio Grande Valley of Texas (Note: Starr County is not shown because there were no irrigation districts that concerned this research.)

DOI: 10.1002/ird

202 ac-ft). Seepage and leakage from irrigation canals are widely recognized as a problem throughout the United States and the world (Fipps, 2000; Etienne, 2003; International Commission on Irrigation and Drainage (ICID), 1967).

Water losses in irrigation distribution canals can occur through several mechanisms, including excess seepage in a canal segment, point leaks from breaks or fissures in the canals or pipelines, and evaporation. Leaks and seepage are generally considered to represent a large majority of the loss. A variety of methods are used for detection of leaks and seepage, including measurement of pressure or flow rate change (Tucciarelli *et al*., 1999; Paquin *et al*., 2000), acoustic signal analysis of running water (Hunaidi and Chu, 1999), and radar detection of soil moisture content (Hunaidi and Giamou, 1998). These methods may be costly, time-consuming, often do not precisely locate leaks, and are labour-intensive, especially considering the large command areas of many irrigation districts.

Remote sensing has shown promise as a tool for quick and cost-effective detection of leaks in aqueducts (Nells, 1982; Pickerill and Malthus, 1998). One limitation is the resolution which is required (within a few meters at most) in order to detect canal leakage. Earth-observing satellite systems are limited in the spatial resolution. For example, low-resolution satellite systems such as the National Oceanic and Atmospheric Administration (NOAA)'s Advanced Very High Resolution Radiometer (AVHRR) and Terra-Moderate Resolution Imaging Spectro-radiometer (MODIS) are applicable only to regional-scale studies. The spatial resolutions of other satellite systems, such as the National Aeronautics and Space Administration (NASA)'s Terra-Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Landsat 7 Enhanced Thematic Mapper (ETM), and China Brazil Earth Resources Satellite (CBERS), only range from 30 to 100 m. Currently, high-resolution satellite imagery is available in visible and NIR wavelengths from systems such as IKONOS (GeoEye, Dulles, Virginia, USA) and QuickBird (DigitalGlobe, Longmont, Colorado, USA). However, there are no civilian high-resolution thermal infrared satellite systems currently operating, nor are any planned for the near future.

Airborne remotely sensed thermal imagery has been used in detection of canal leaks. The most well- known study was conducted in central Oregon, USA, in 1979 for the North Unit Irrigation District using thermal infrared imaging (Nells, 1982). Of 39 sites identified as having possible leakage areas, 12 were verified through field analysis, representing 31% detection accuracy. No additional leakage sites were discovered beyond the 12 labelled on the imagery; in other words, while there were false positives identified in the images, there were no false negatives detected. The causes of image misinterpretation were attributed to the occurrence of dense natural vegetation, farm canals, and drainage ditches located adjacent to the canals, and the presence of small holding ponds and low depression areas of natural drainage. The author concluded that despite the low detection accuracy, the amount of time saved by only checking the positive sites on the image rather than the entire canal system for leakage was significant.

Pickerill and Malthus (1998) analyzed two known leaks and found that different indices and single bands were required in order to identify each leak. The spectral profile of one leak responded best to a ratio of NIR to red reflectance, while in the other, NIR to red reflectance ratio was not useful in differentiating the second leak from its surroundings. Thermal image data were also examined for their ability to distinguish the leaks from their surroundings, but the authors found no significant temperature differences between the leaks and their surroundings.

MATERIALS AND METHODS

Equipment

The airborne multispectral remote sensing imager was assembled by integrating commercially available imaging and computer components and combined high-performance, high-resolution imaging sensors in the visible, NIR, and thermal infrared wavelengths. Components included a 12-bit (4096 discrete levels) infrared digital camera of Indigo Systems Merlin (Niceville, Florida, USA), two 12-bit Dalsa 1M30 digital cameras (Waterloo, Ontario, Canada) for visible and NIR imagery, and astronomy-grade interference filters for the red (0.66 micron) and NIR (0.8 micron) wavelengths (Figure 2). The image data from all three cameras are captured with a PCI-bus computer with two Bitflow Roadrunner digitizing boards.

DOI: 10.1002/ird

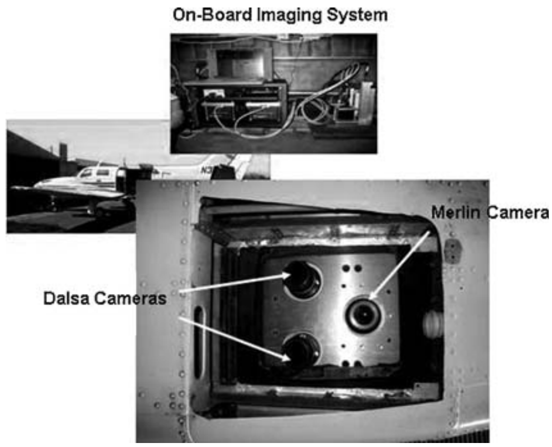

Figure 2. Components of the airborne multispectral imaging system

During the flyover, a small camcorder is used to provide a real-time, true-colour display of the general area being imaged which enables the operator to more easily recognize landmarks during an imaging mission and give directions to the aircraft pilot regarding adjustments to the flight track.

Experience with the imager has shown that a spatial resolution of 1–2 m can be achieved when the system is flown aboard a light aircraft at an altitude of approximately 1500 m which is appropriate for leak detection in canal systems.

Image processing

As the aircraft flies over a canal segment, a series of image triplets are recorded along with the time and location (latitude and longitude). Commercial imaging software (ERDAS Imagine, Leica Geosystems Geospatial Imaging) was used to process the imagery as follows:

1. Convert file format from RAW to IMG.
2. Register images into a single coordinate system.
3. Stack the three registered red, NIR, and thermal images into a composite image.
4. Georeference the images using ground control points to allow use with GIS-based maps and images.
5. Image Area of Interest (AOI) generation.
   This function is employed to clip the images into the (AOI).
6. Normalized Difference Vegetation Index (NDVI) image generation

Based on the AOI composite image, the NDVI image can be generated as:

$$\text{NDVI} = (\text{NIR} - \text{Red})/(\text{NIR} + \text{Red})$$

NDVI has been widely used for remote sensing of vegetation (Jensen, 1996).

The image-processing software allows the steps such as image format conversion, image stacking, and NDVI image generation to be performed automatically. However, we found that it was simpler and faster to complete other steps, such as image registration, image georeference, and AOI image generation manually.

Field reconnaissance

A site evaluation rating was conducted at 40 selected sites based on the following protocol:

1. Prepare a GIS map to cover the concerned sites.

DOI: 10.1002/ird

2. Conduct field evaluation along with canal section rating with pre-designed criteria.
3. Complete the analysis.

The pre-designed criteria used to rate the conditions at each canal site are as in Table I.

RESULTS

On February 28, 2005, we conducted a flyover with the imaging system and acquired multispectral imagery of 24 canal sections located within 11 irrigation districts (Figure 3). The flight altitude was 914 m (3000 ft) above ground level, resulting in a spatial resolution of 0.64 m (2.1 ft) per pixel for the red and NIR images and in a spatial resolution of 2.07 m (6.8 ft) per pixel for the thermal imagery. Four hundred and thirty-nine image triplets (439 red, 439 NIR, and 439 thermal images) were obtained during the mission. Fifteen and nine lined and unlined canals, respectively, were present in the 24 sections.

After the overflight, 140 of the 439 imaged canal sites were identified as having possible canal leakage problems (point leak and/or seepage). The image triplets from the 140 sites were processed for further analysis.

Field reconnaissance verified that 26 of the 28 sites inspected had leakage problems (Table II), representing a 93% success rate of image analysis. Three of the leak sites were considered to have major leakage problems. The following three case studies provide details on the sites and interpretation of the imaging.

Case 1

Case 1 is a concrete canal section in the Delta Lake Irrigation District (Site 3 in Table II). Red and NIR images indicated a wide drainage area along the canal (Figure 4) and a significant amount of vegetation on the canal levees. The NDVI image, which enhances the signatures of the vegetation, showed significant vegetation on the levees and in the drainage ditch (bright part on the image), and bare soil (i.e. no crops) in the adjoining fields. The thermal image presents a much cooler signature at a location on the south (bottom) side of the canal than in the adjacent area (circled in Figure 4), which is likely the location of a leak.

Table I. Pre-designed criteria for canal condition rating

Factor		Rating	Definition
Wetness		0	Not visible
		1	Some visible
		2	Severe
Vegetation	Grass	0	None
		1	Some
		2	Dense and thick
	Tree/bush	0	None
		1	Some
		2	Strong and big
Seepage		0	None
		1	Some
		2	Severe
Cracks		0	None
		1	Some
		2	Large and severe
Holes		0	None
		1	Small
		2	Large

DOI: 10.1002/ird

Figure 3. GIS map of scanned canal sections in the overflight and visited sites in field reconnaissance

Table II. Field visual rating results of typical cases in field reconnaissance

Site	Type	District	Wetness	Grass	Tree/bush	Seepage	Crack	Hole	Total	Leak/seepage?
1	Lined	Delta Lake	0	2	2	1	1	0	6	Yes
2	Lined	Delta Lake	0	2	2	1	1	0	6	Yes
3	Lined	Delta Lake	2	2	1	1	2	0	8	Yes[a]
4	Lined	Delta Lake	0	2	2	1	2	0	7	Yes
5	Lined	Delta Lake	0	2	2	1	2	0	7	Yes
6	Lined	Delta Lake	0	2	2	1	1	0	6	Yes
7	Lined	Delta Lake	0	2	2	1	1	0	6	Yes
8	Lined	Delta Lake	0	2	2	1	2	0	7	Yes
9	Lined	Delta Lake	0	2	2	1	2	0	7	Yes
10	Lined	Delta Lake	0	2	2	1	2	0	7	Yes
11	Lined	United	1	2	1	1	2	0	7	Yes
12	Lined	United	1	2	2	1	2	0	7	Yes
13	Lined	United	2	2	2	1	2	0	9	Yes[a]
14	Lined	United	2	1	2	1	1	0	7	Yes
15	Unlined	San Benito	2	2	0	1	0	2	7	Yes[a]
16	Unlined	San Benito	2	2	0	1	0	2	7	Yes
17	Unlined	San Benito	1	2	0	1	0	1	5	Yes
18	Unlined	San Benito	1	2	0	1	0	1	5	Yes
19	Unlined	Harlingen	0	2	2	1	0	1	6	Yes
20	Unlined	Harlingen	1	2	0	2	0	1	6	Yes
21	Unlined	Harlingen	1	2	0	1	0	1	5	Yes
22	Lined	Harlingen	1	1	0	0	0	0	2	No
23	Lined	Harlingen	1	1	0	0	0	0	2	No
24	Lined	United	0	1	2	1	2	0	6	Yes
25	Unlined	Edinburg	1	2	2	1	0	1	7	Yes
26	Unlined	Edinburg	1	2	2	1	0	1	7	Yes
27	Lined	San Juan	1	2	0	1	1	0	5	Yes
28	Lined	Donna	1	2	0	1	1	0	5	Yes

[a]The site is considered to have a major leak and/or seepage problem.

DOI: 10.1002/ird

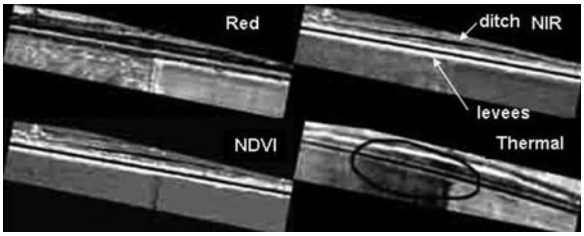

Figure 4. Airborne multispectral images of a concrete canal section in the Delta Lake Irrigation District (Case 1). The circled area in the thermal image showed a significantly cooler area – a large missing piece of concrete lining resulting in a major leak

Figure 5 shows a ground-level photo of Site 3. The wide drainage area was on the north (right) side of the canal section under the thick bushes. The canal section appeared to be in fairly good condition. The grass on the levees is an indicator of seepage from the canal. The actual leak is located on the south (left) side of the canal and consisted of cracks and a large missing piece of concrete lining and corresponds to the thermal image indicator shown in Figure 4. Conclusions of the field reconnaissance were that there were both a major leak here and high levels of seepage as indicated by grass and bushes present in the area.

Case 2

The second case study illustrates the usefulness of using multispectral images in order to filter out false positives. Site 4 (Table II) is also a concrete canal segment in the Delta Lake Irrigation District. The red, NIR, and thermal images (Figure 6) indicated that the canal section was in fairly good condition, with two areas indicating possible problems. On the red and the NIR images, the circled areas represent dense vegetation, whereas, on the thermal image, they represented areas of low temperature, which may be related to wetness. However, the corresponding NDVI image generated from the red and NIR images revealed a large tree and its shadow between the tree and the canal. Also, the NIR image indicates dense vegetation along the levee and in the adjacent area, a signature of seepage.

This interpretation was confirmed during field reconnaissance as shown in the ground-level photograph (Figure 7) which shows the canal segment in fairly good condition. The photograph also shows the tree and shadow which is not related to the seepage or leakage, and the vegetation which indicates seepage problems. This case explained how images obtained in other regions of the spectrum help avoid misleading information provided by the thermal image.

Figure 5. Ground-level photograph of a concrete canal section in the Delta Lake Irrigation District (Case 1)

DOI: 10.1002/ird

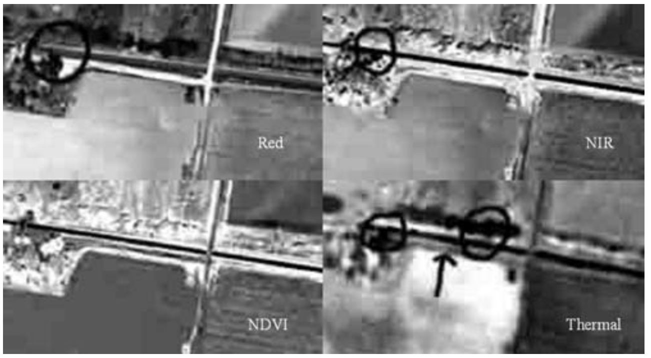

Figure 6. Airborne multispectral images of a concrete canal section in the Delta Lake Irrigation District (Case 2). The circled areas in the images show dense vegetation and surrounding areas, which was proven to be a tree and its shadow. NDVI with NIR and red images could differentiate the tree and shadow, but the thermal image could not

Case 3

The third case illustrates a different type of problem which is easily identified through image analysis. Site 20 (Table II) is an unlined canal segment in Harlingen Irrigation District. While the canal segment appears to be in good condition (Figure 8), the red image indicates some sort of structure or artefact around the circled area, and the thermal image shows a low temperature signature here as well. The wavy line in all four images indicates dense vegetation in this area.

Field reconnaissance gave the site a visual rating of 6, meaning that the site may have a problem with a leak. The ground-level photograph (Figure 9) verifies that the canal segment was in fairly good condition, and grass grew uniformly along the sides of the channel (wavy lines in Figure 8). The circled area in the figure was a structure (i.e. a standpipe and valve) used to divert water into a pipeline system. Some seepage was occurring on the east side of the building as indicated by the imagery. The seepage was caused by the operation of the structure. It was concluded that a seepage problem existed at this site. It was mainly caused by the operation of the water distribution system.

DISCUSSION

Through a quick review of the raw image data, 32% of the imaged canal sites were identified as having possible canal leakage problems (140 out of 439 sites). After the batch image processing with ERDAS Imagine and the analysis of the processed images, field reconnaissance was conducted at 28 selected image sites. A 93% rate of success was achieved for leak detection in canal systems based on image analysis.

Figure 7. Ground-level photograph of a concrete canal section in the Delta Lake Irrigation District (Case 2)

DOI: 10.1002/ird

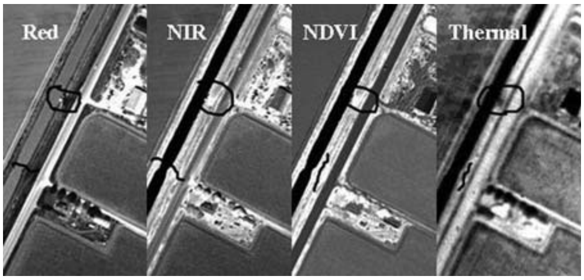

Figure 8. Airborne multispectral images of an earth canal section in Harlingen Irrigation District 2 (Case 3). The circled location was a standpipe structure and the marked lines showed dense vegetation

With the high detection accuracy, time is saved because the researcher, engineer, and district personnel only have to check the specific sites suspected to have problems on the imagery rather than the entire distribution network for leakage.

The method of airborne multispectral imaging we developed preserves the advantages of thermal imaging in canal leak detection. At the same time the method is able to eliminate misleading results obtained on individual thermal imagery by using visible, NIR, and NDVI images. The thermal imaging techniques can be used to generate images that represent the surface temperature distribution over the scenes. Leaks of the canals can be detected by evaluating the temperature distribution around canal sites. Water and wet areas have different temperature signatures than surrounding soil, structures, and vegetation. However, just using thermal imaging can lead to false positives as in Site 4 where a tree and its shadow caused a low temperature signature. Case 2 was a classic example of the benefits that could be achieved with the multispectral approach. Consistent and accurate results were obtained with the techniques used in the study.

When the method was applied, the cost was considered. Currently there are no commercially available airborne remote sensing systems that contain cameras for acquiring imagery in the visible, near-infrared, and thermal infrared wavelengths. A number of research systems have been developed with these capabilities, including the one used in the research of this paper. This system contains commercially available cameras, computers, and other components that have been integrated to produce working remote sensing systems with the required capabilities. The main costs of the system are the cameras, filters, frame-grabber boards, computers, and the cost of integrating the system (essentially writing software to make the components function as a system). For the thermal infrared, 12-bit thermal cameras that operate in the 10 micron range, such as the Merlin, the cost is around US$20K, with an additional US$4K for the lenses. There are a wide variety of 12-bit digital monochrome cameras that, when fitted with the appropriate filter, can acquire imagery in the visible and near-infrared wavelengths. Cameras such as the Dalsa 1M30 cost around US$10 000. A high-quality interference filter will cost around US$2500.

Figure 9. Ground-level photograph of an earth canal section in Harlingen Irrigation District 2 (Case 3)

DOI: 10.1002/ird

Frame-grabber boards, which are installed in the computer to capture imagery from the cameras, cost around US$2000 each. A ruggedized computer will cost around US$6000. Finally, if users do not do the integration themselves, they will need to hire a software integration company to put all the components together and write software to control the system. This cost was around US$20 000. So, to produce a complete, working system with thermal, visible, and near-infrared imaging capabilities (one thermal camera and two monochrome digital cameras) described in this paper, the total cost would be around US$60 000 for the hardware and US$20 000 for the integration costs.

The scale of project was also considered. Basically, there are two scales of project:

1. *Local scale*: this is for quick assessment of canal leaks in a length up to 400 m with possible site-specific measurements.
2. *Area scale*: this is for assessment of canal leaks in a length from hundreds of meters to tens of kilometres.

The working procedure of this research was to use airborne remote sensing to scan the irrigation system at area scale and then after processing and evaluating the imagery, field reconnaissance was conducted at local scale to validate.

Some operational constraints should also be considered. The method of airborne remote sensing is operational over the canal sections as long as the irrigated area is less than 10 m from the canal, which was the case in the research.

CONCLUSIONS

Airborne multispectral imaging is very promising as a tool in detection of irrigation canal leakage in distribution networks. The analysis of the processed image data from red, NIR, and thermal bands is highly consistent with the observations from field reconnaissance. The images from individual bands, particularly from the thermal band, can help characterize leakage in irrigation canals. The NDVI image which combines the data from the red and the NIR bands can help detect and correct errors observed on the thermal imagery.

The method proposed in this study is a timely and cost-effective approach to determining the leakage of irrigation canals in distribution networks. It has the advantage of having the capability to evaluate the surrounding conditions of canals related to leaks and seepage at the same time in the region. This newly developed method has been proven successful in rapidly providing high-resolution imaging data, detecting leaks, and determining potential seepage of irrigation canals in distribution networks in the LRGV of Texas. It should have widespread application. In practice the success of this method will produce informative data regarding leaks supplied to the irrigation districts, which will lead to increased water availability and better management of water use and allocation.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Mr Eric Leigh and Mr Askarali Karimov. They are Extension Associates of Texas Cooperative Extension. Mr Leigh worked on the plan of the overflight and provided a GIS map for the pilot and imager operator. Mr Karimov provided great help in field monitoring together with Mr Martin Barroso, GIS technician of Texas Cooperative Extension. He also greatly helped in field reconnaissance. The authors would also like to thank Mr Rene Davis of the USDA-ARS Remote Sensing Group in Weslaco, who operated the plane for the overflight. This work was partially funded with support from the Rio Grande Basin Initiative supported by USDA-Cooperative State Research, Education, and Extension Service and administered by the Texas Water Resources Institute.

REFERENCES

Etienne G. 2003. The economy of seepage and leakage in Asia: the most dangerous issue. In *Fighting Corruption in Asia: Causes, Effects and Remedies*, Kidd J, Richter FJ (eds). World Scientific: Hackensack, NJ; 221.

DOI: 10.1002/ird

Fipps G. 2000. Potential water savings in irrigated agriculture for the Rio Grande planning region (region M). Texas Cooperative Extension, Texas A&M University System.

Hunaidi O, Chu WT. 1999. Acoustical characteristics of leak signals in plastic water distribution pipelines. *Applied Acoustics* **58**: 235–254.

Hunaidi O, Giamou P. 1998. Ground-penetrating radar for detection of leaks in buried plastic water distribution pipes. 17th International Conference on Ground-Penetrating Radar, Lawrence, USA.

International Commission on Irrigation and Drainage (ICID). 1967. *Controlling Seepage Losses from Irrigation Canals: World Wide Survey.* New Delhi, India.

Jensen JR. 1996. *Introductory Digital Image Processing*. Prentice Hall: Upper Saddle River, NJ, USA.

Nells MD. 1982. Application of thermal infrared imagery to canal leakage detection. *Remote Sensing of Environment* **12**: 229–234.

Paquin F, Babineau D, Brisette F, Leconte R. 2000. Development of a methodology for locating leaks in water lines. *Canadian Journal of Civil Engineering* **27**: 151–159.

Pickerill JM, Malthus TJ. 1998. Leaks detection from rural aqueducts using airborne remote sensing techniques. *International Journal of Remote Sensing* **19**(12): 2427–2433.

Tucciarelli T, Criminsi A, Termini D. 1999. Leak analysis in pipeline systems by means of optimal valve regulation. *Journal of Hydraulic Engineering* **125**: 277–285.

Texas Water Development Board (TWDB). 2002. 2002 State Water Plan. http://www.twdb.state.tx.us/publications/reports/StateWaterPlan/2002/WaterforTexas2002.pdf

DOI: 10.1002/ird