Evaluation of canal lining projects in the Lower Rio Grande Valley of Texas

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2013 Rating and Analysis

Rio Grande Basin Initiative
Irrigation Technology Program
Texas A&M AgriLife Extension Service

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EXECUTIVE SUMMARY

Since 1999, nine (9) irrigation districts in the Hidalgo, Cameron, Willacy and Maverick Counties have installed ten (10) different types of synthetic canal lining materials, totaling approximately 25 miles. In 2005, we began a program to track the long-term effectiveness and durability of these lining projects and to document the damage caused by such factors as weather, animals, intentional and unintentional vandalism, farm machinery traffic, and normal irrigation district operation and maintenance activities. We visually inspected each project and documented any changes using a lining evaluation form which we developed.

For analysis purposes, we grouped all the projects into two general categories: liners with a protective barrier, and liners without a protective barrier. The projects with a protective barrier performed very well. The synthetic liner is underneath and is designed to reduce seepage while the shotcrete layer, on top, protects the liner from damage. This lining system needed little maintenance. There were two types of liners used, PVC and polyester, and both performed well.

The performance of synthetic liners without a protective barrier varied dramatically. High variation of performances indicates that there is potential for good performances, but some conditions must be met. One important factor was the location of the project. Liners located in high traffic areas (people and animals) showed significantly more damage than those installed in remote areas. Damage caused by mowing and canal cleaning operations was common, and consequences of this damage varied for each liner. Liners carelessly or improperly installed were more susceptible to damage. For example uneven and collapsing anchors caused major damages, especially with shrinking materials.

Among liners without a protective barrier, the PVC Alloy is the toughest material, is more difficult to cut and less likely to be damaged by unintentional vandalism. Nevertheless, its high shrinking tendency needs to be taken into consideration at installation. The reinforced rubber liners installed in 2009 have performed very well so far. A new material (multi-layer polyethylene) was installed in 2012 in locations with high traffic, and looks promising because is easy to install and resistant to tears. A summary of the factors affecting materials performance is given in Table A-6.

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INTRODUCTION

Since 1999, irrigation districts in Hidalgo, Cameron, Willacy, and Maverick Counties have been experimenting with an assortment of canal lining materials installed in about 25 miles of earthen and concrete canals. In 2005, we initiated a program to track the long-term effectiveness and durability of these materials and to document installation and maintenance procedures which will help ensure good performance.

Each lining project was periodically inspected to document the effects of such factors as weather, animals, intentional and unintentional vandalism, farm machinery traffic, and normal irrigation district operational and maintenance activities. Evaluation forms were developed and improved every year, and are organized with a three stage approach: a general project description, a district operations questionnaire, and a field observation and rating survey. This three staged approach is designed to identify the size, location, and causes of damage.

In this report we present an update of previous reports (Karimov et al., 2009, Bonaiti et al., 2011) with the 2013 field inspection, and a summary of the results from the first nine (9) years of inspections.

MATERIALS AND METHODS

Lining Materials and Projects Location

The following types of lining materials have been installed in nine (9) irrigation districts in Hidalgo, Cameron, Willacy and Maverick Counties:

1. Polyester with a shotcrete protection barrier
2. PVC with a shotcrete protection barrier
3. Polypropylene
4. PVC alloy
5. EPDM rubber
6. Polyurethane
7. Green TPO-R
8. Reinforced EPDM
9. Reinforced FPP-R
10. Multi-layer Polyethylene

The liners with a protective barrier were used on unlined canals. The remaining liners were installed on concrete canals. Table 1 provides a generic description of each material. Locations of projects are shown in Figures 1-5. In 2012, projects 14, 17 to 21, and part of 25 in the Hidalgo County Irrigation District No. 1 were removed and replaced by projects 34-36 (Fig. 2 and 3). Complete information on installation date, extent, and other details for each project are given in Tables A- 1 and A- 2.

Table 1. Description of each lining material's composition

Material	Description
Polyester with protective barrier	A geocomposite consisting of two layers (top and bottom) of 8 oz/yd2 nonwoven polyester bonded to an olefinic copolymer geomembrane, 20 mil thick. The protective barrier consists of 2-3 inches of shotcrete
PVC with protective barrier	Non-reinforced Poly Vinyl Chloride (PVC). The protective barrier consists of a wire mesh with 2.5 inches of shotcrete
Polypropylene	A reinforced polyester scrim 16 oz/yd2 between polypropylene layers, 24 mil thick
PVC Alloy	A polyvinylchloride blend, reinforced with a polyester scrim, 40 mil thick
EPDM Rubber	A non-reinforced EPDM (ethylene propylene diene monomer), 45 mil thick
Polyurethane	Two layers of 3-oz/yd2, heat-bonded, non-woven geotextile saturated with liquid polyurethane, 40 mil thick
Green TPO-R	A reinforced TPO Geomembrane (flexible thermoplastic polyolefin membrane), 60 mil thick
Reinforced EPDM	A reinforced EPDM (ethylene propylene diene monomer), 45 mil thick
Reinforced FPP-R	A reinforced fPP (polypropylene/rubber-based geomembrane), 45 mil thick
Multi-layer Polyethylene	A 20-mil thick polyethylene geomembrane bonded to two 8-oz/yd2 non-woven geotextile layers (top and bottom)

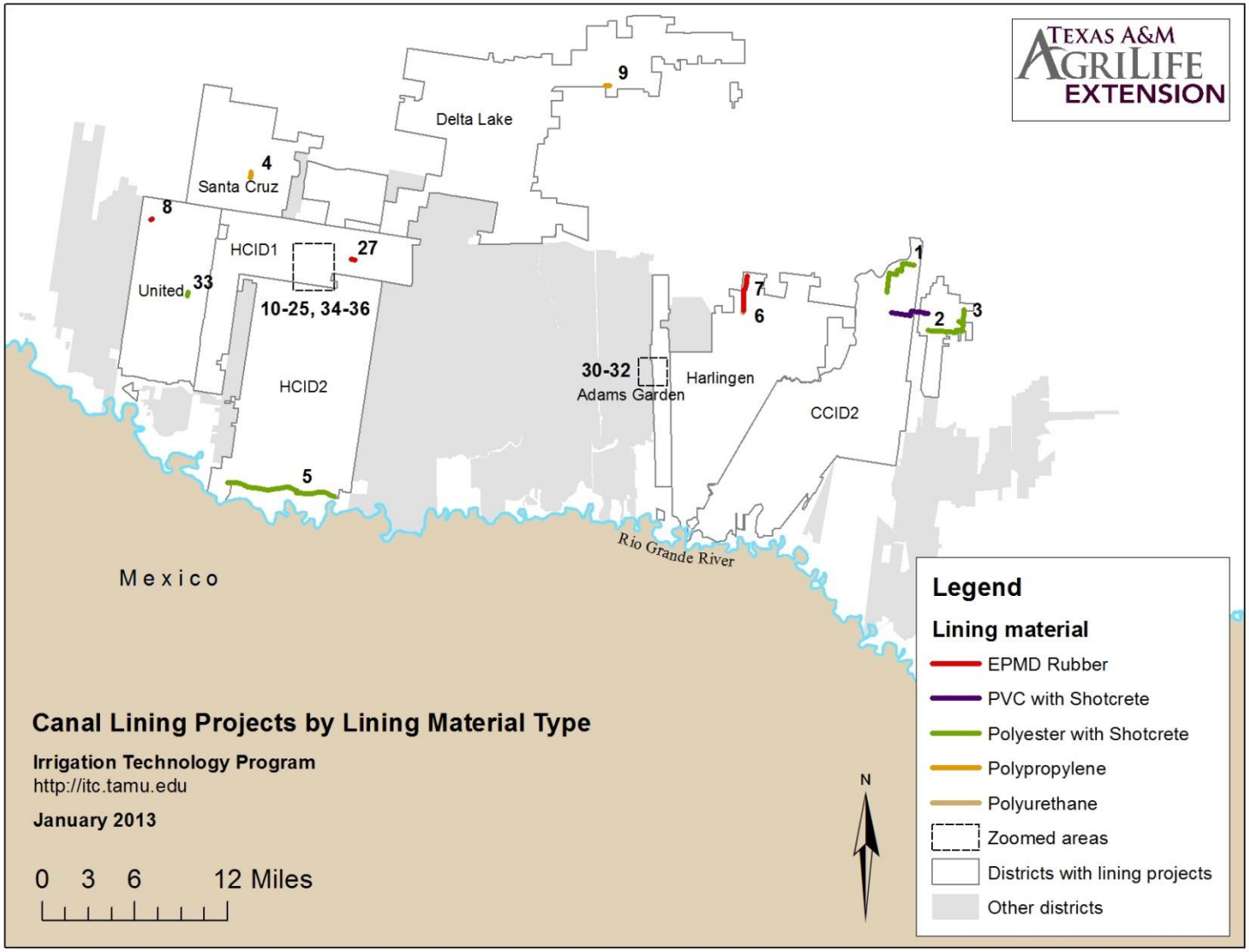

Figure 1. Lining Projects by Material Type in the Hidalgo, Cameron, and Willacy Counties

Figure 2. Lining Projects by Material Type in the HCID1 Zoomed Area until 2011

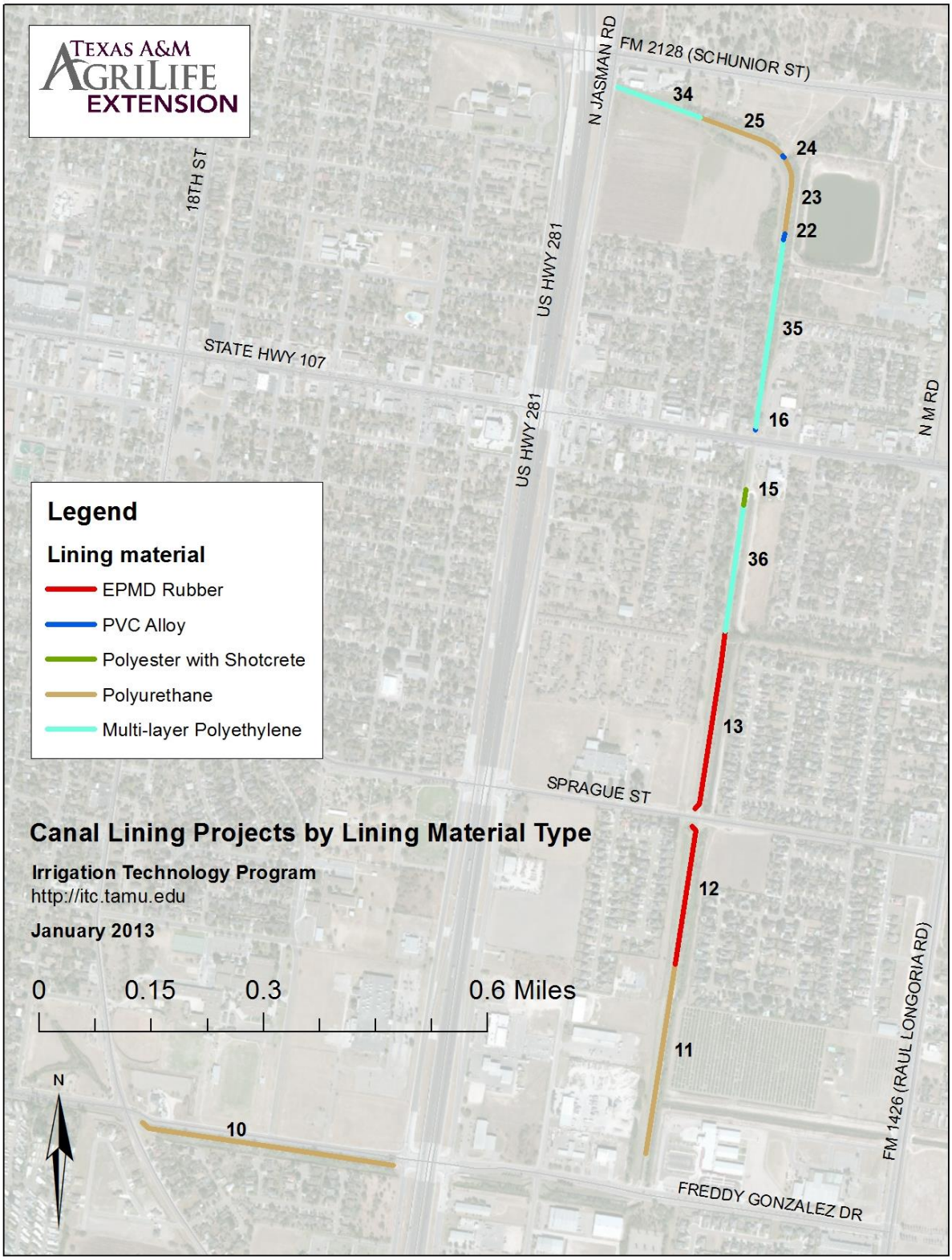

Figure 3. Lining Projects by Material Type in the HCID1 Zoomed Area since 2012

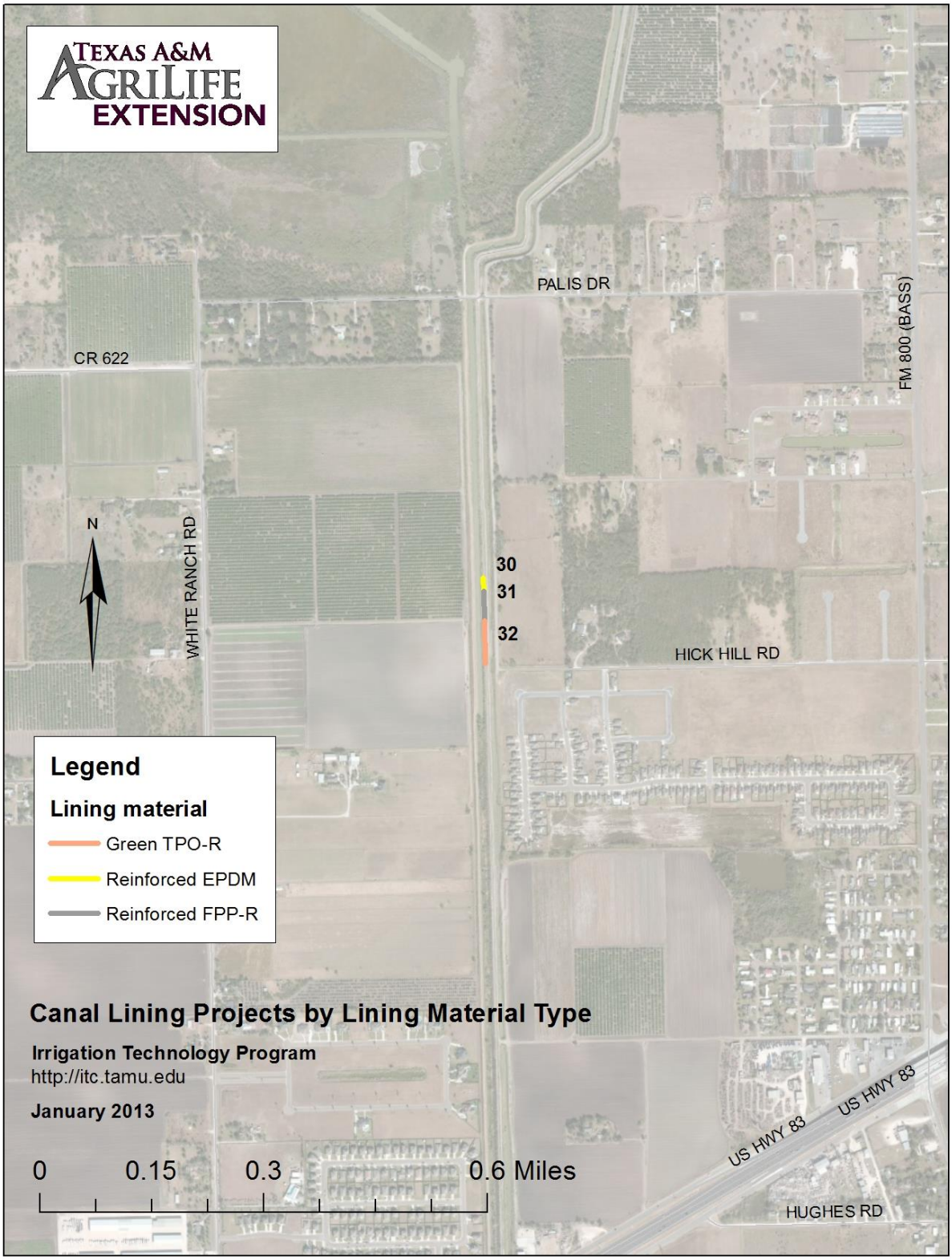

Figure 4. Lining Projects by Material Type in the Adams Garden Zoomed Area

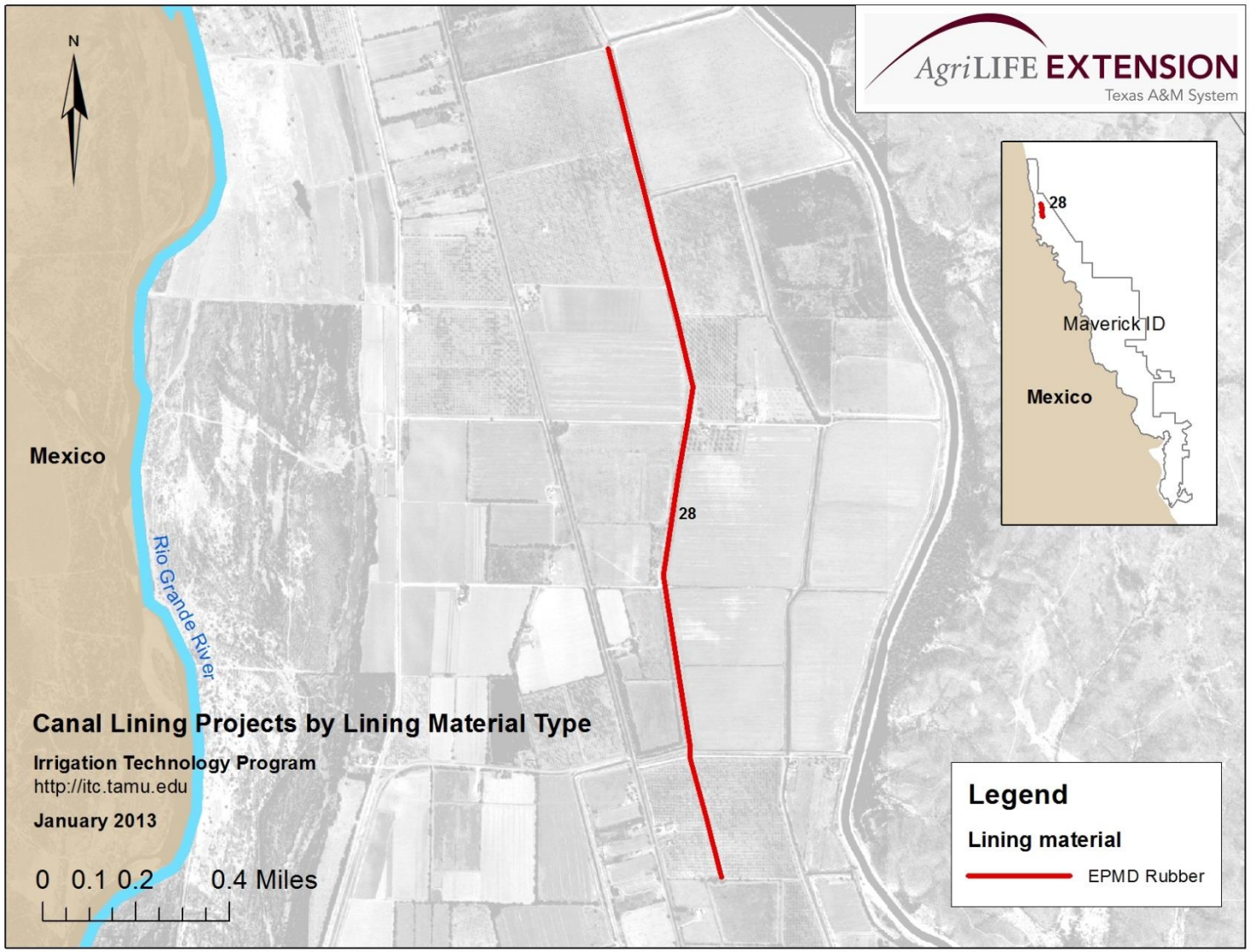

Figure 5. Lining Project in the Maverick County

Evaluations and Field Inspections

In 2013 we updated the general project description and the district operation questionnaire only relatively to the projects installed with new material, as no other changes occurred since 2011 for the other projects. Field inspections were conducted during the winter months, which have proven to be the most effective as water levels tend to be the lowest during this time of the year. Projects were visually inspected looking at several parameters, which included counting or measuring, assigning percentage or rating classes, and identifying locations of damages. A rating based on the overall general condition was given to each project, and ranged from *Excellent* to *Serious Problems.* The criteria used to assign this rating are listed in Table 2. We used the same field data sheets used in 2011, which are different for exposed synthetic liners and liners with a protective barrier. Copy of the field data sheet can be found in the 2011 report (Bonaiti et al., 2011).

Rating was completed separately for the anchor, free board, and wetted area (Fig. 6). For projects No.1, 2, 5, and 7, which are very long, we maintained the subdivision in shorter sub-projects as identified in 2011, and we completed a data sheet for each one. For these projects, the general rating is the arithmetic average of the ratings of all sub-projects. In this report the age of a liner is calculated counting the year of installation and the years of rating, regardless the actual months. Therefore, for example, if a liner has been installed in 2012, in our 2013 rating we will consider that the liner is 2 years old.

Table 2. Overall general condition rating for canal liners

Rating	Performance
Excellent	No damage
Good	Minor damage appeared on the anchor and the free board. The damage may affect the rest of the liner if not repaired in a timely manner
Fair	Minor damage appeared on the wet wall of the canal. The damage may affect the rest of the liner if not repaired in a timely manner
Poor	Major damage appeared on the anchor area and the free board section. Most of the section has some damage
Serious Problems	Major damage appeared in the wet area. In some cases all or part of the liner has been removed

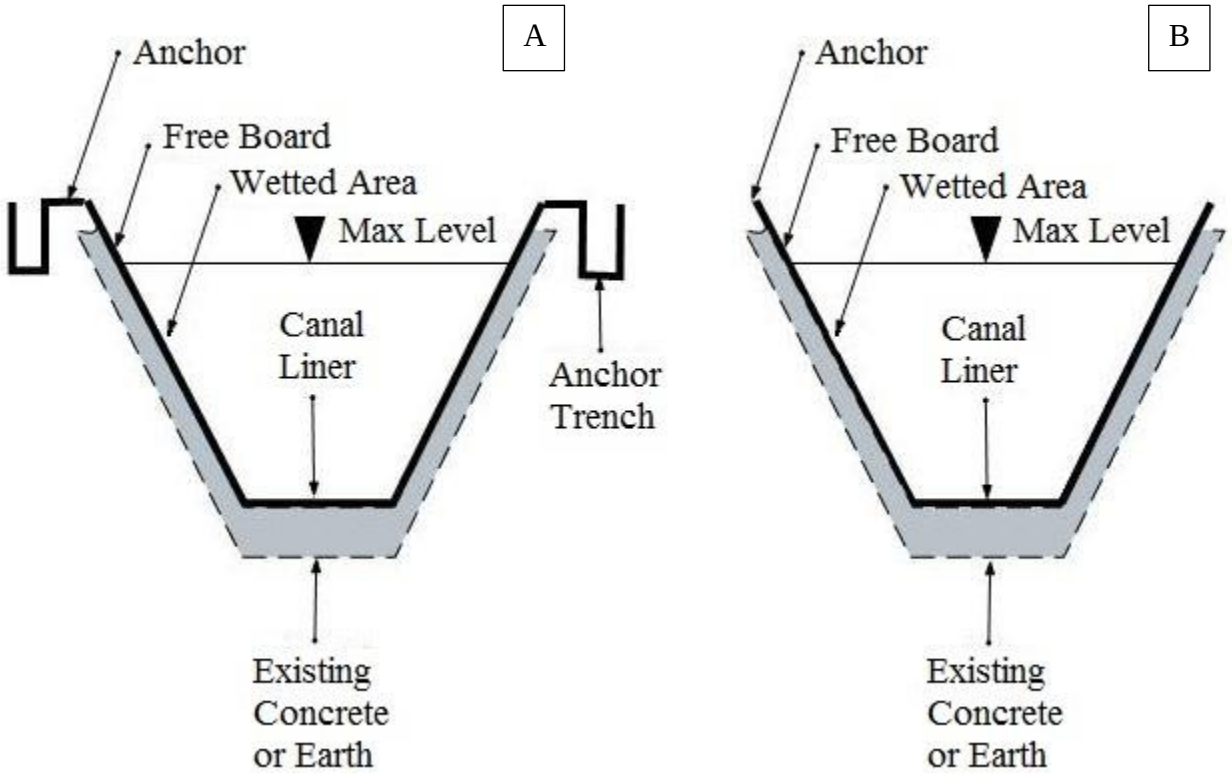

Figure 6. Ratings were completed separately for the anchor, free board, and wetted area. A) Liner with anchor trench; B) Liner without anchor trench

RESULTS AND DISCUSSION

Liners with a protective barrier performed very well and have required little maintenance, while the performance of the liners without a protective barrier has varied dramatically. The range of ratings given to projects in 2013, grouped by lining material, is reported in Table 3.

Table 3. Range of average overall general condition rating by lining material in 2013

Material	No. of Projects	Total Miles	Rating (2013)	Age (years)
With a protective barrier				
Polyester with shotcrete	5	15.03	Excellent to Good	5-10
PVC with shotcrete	1	2.62	Good	9
Without a protective barrier				
Polypropylene	2	0.60	Excellent to Serious Problems	10
PVC Alloy	3	0.02	Good to Serious Problems	15
EPDM Rubber	9	5.01	Good to Serious Problems	9-14
Polyurethane	9	1.35	Fair to Serious Problems	10-15
Green TPO-R, Reinforced EPDM, Reinforced FPP-R	3	0.12	Excellent	5
Multi-layer Polyethylene	3	0.54	Excellent to Good	2

Figure 7 shows the average and standard deviation of yearly ratings, calculated among all projects with the same type of liner and the same age, updated at 2013. In the chart, when data is missing for a certain age we interpolated linearly between the previous and the following available rating, and we did not display any marker. Average ratings in some years slightly improve instead of worsening as expected. This happens because projects have been installed in different years, and number of replicates can be different as age varies.

In the chart, EPDM Rubber, Polypropylene and Polyurethane have always performed worst. Nevertheless, Polypropylene did not decrease its performance in the past four (4) years. A second group of materials, i.e. liners with protective barriers and PVC Alloy, performed somewhat better. Reinforced Rubber, only 5-years old, has showed no decrease in performances (Fig. 7A). Standard deviation for EPDM Rubber and Polyurethane was 0 in 2013, after being rather high at 8-9 years of age. This means that even projects that performed somewhat well at early stages are not effective anymore at 14-15 years of age. Greatest standard deviation is found with Polypropylene, but there are only two projects with this material, and one of them failed due to the collapse of the canal walls. High standard deviation indicates that there is potential for good performances, but some conditions must be met (Fig. 7B).

Ratings of individual projects and sub-projects are given in Tables A- 3 and A- 4, and the calculation of yearly averages for each project is given in Table A- 5.

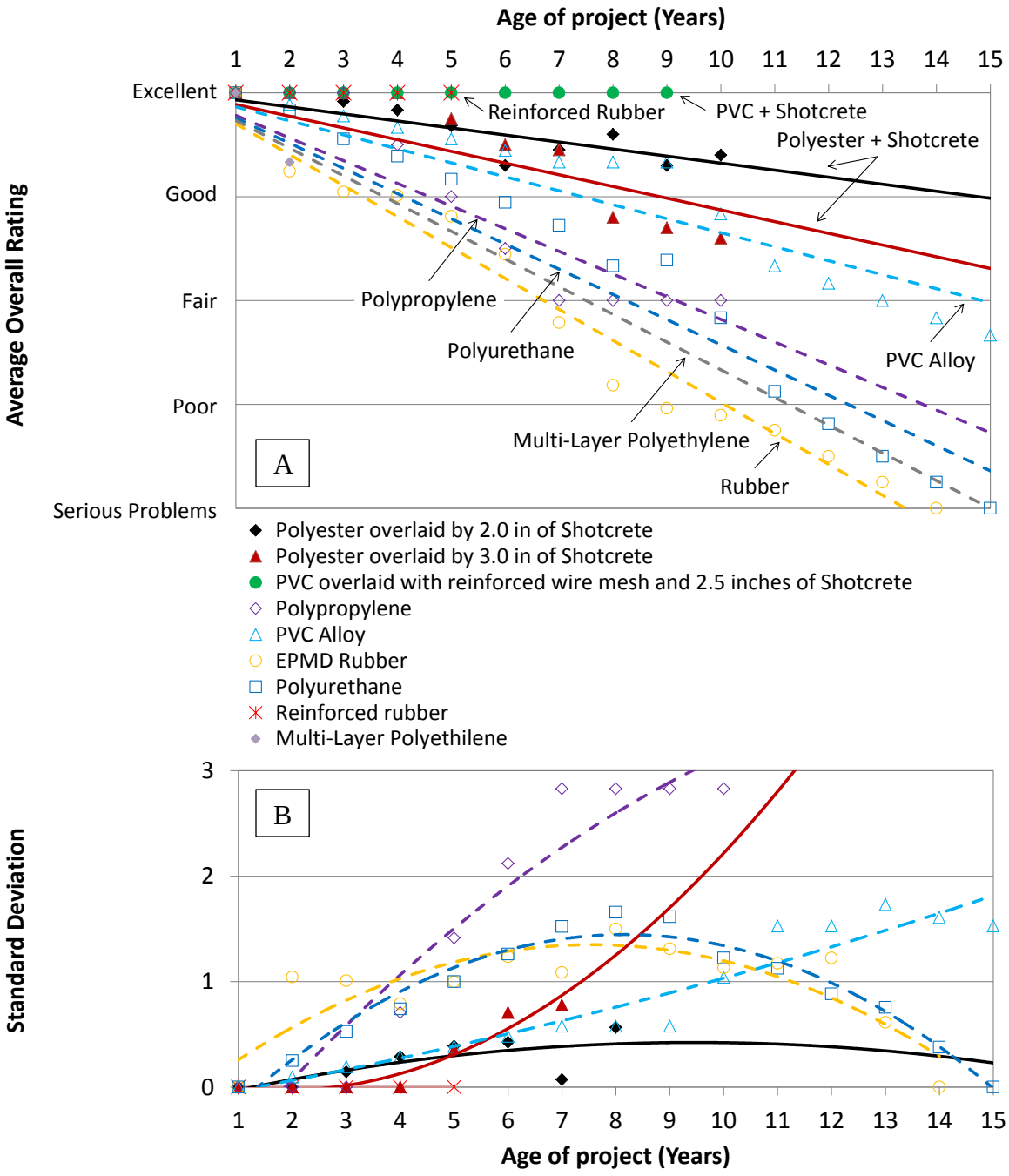

Figure 7. Overall general condition rating averaged for each material, and trend lines. A) Average; B) Standard Deviation

We grouped materials that have similar yearly performances, and fitted the data with regression lines (Fig. 8). EPDM Rubber, Polypropylene and Polyurethane performances decrease at a linear rate of one (1) rating class every three (3) years. Liners with protective barriers and PVC Alloy performances decrease at a linear rate of one (1) rating class every six-seven (6-7) years. Reinforced Rubber has no decrease. Regressions lines were tested for parallelism and the slopes resulted different from each other at a highly significant level (Fig. 8A.) Standard deviation data were well fitted by polynomial regressions of second order (Fig. 8B).

Poor installation and vandalism had a major effect on the performances of liners. These problems occurred only in some locations, and their effects are in large part unrelated to the type of liner, therefore they introduced high variability in the results. We made some changes to the data used for the statistical analysis in order to remove the effect of these factors. In the 2011 and 2013 field evaluation forms, the observations related to liner installation and vandalism were:

- Unevenness of dirt under anchor: percentage class
- Canal wall structural problems: percentage class
- Anchor coming out of entrenchment: percentage class
- Is vandalism one of the causes of damage

We decided to remove the effect of these factors in our statistical analysis by eliminating the projects affected by these factors. A disadvantage of this procedure is that reducing the number of replicates of the same type of liner, we reduced the statistical significance of results.

By eliminating the projects affected by poor installation and vandalism, we obtained much higher performances for all materials, especially polypropylene (we eliminated the project with serious problems) and rubber. Rubber is a material very affected by vandalism, and its performances after a quick initial drop remained rather constant throughout the entire period. Polyurethane confirmed to be the project with major problems in the long term, the only one rated as Poor at the 15^{th} year of age (Fig. 9A). The variability of performances within the same material did not change dramatically in values and trends compared with what found for the average values. This was not the case of rubber, which increased in the first years and decreased much earlier at the 9^{th}-10^{th} year. Standard deviation could not be calculated for Polypropylene and PVC overlaid with shotcrete, as only one project was left after selection in both cases (Fig. 9B.)

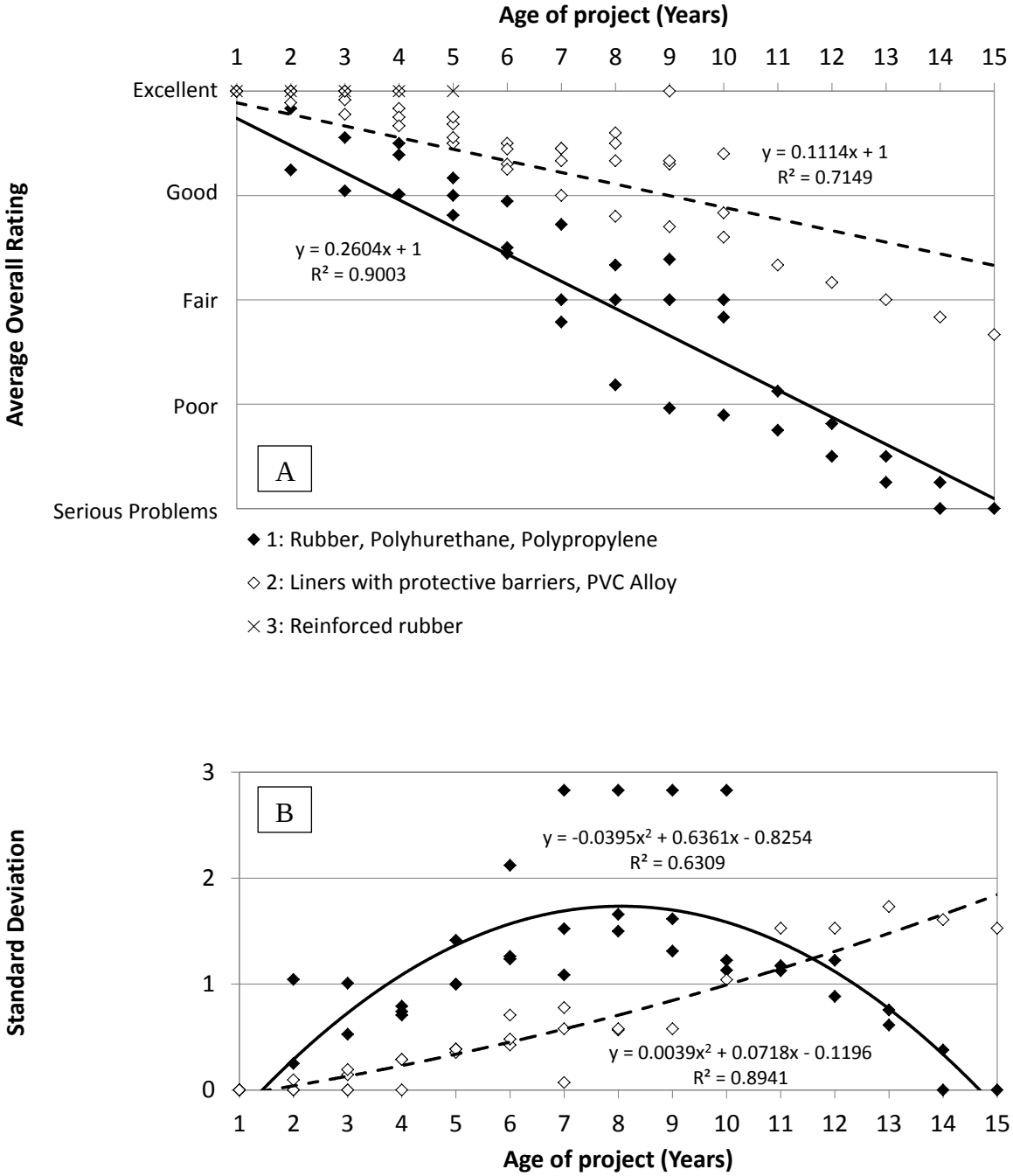

Figure 8. Yearly performance by groups of lining materials and regression analysis. A) Average; B) Standard Deviation

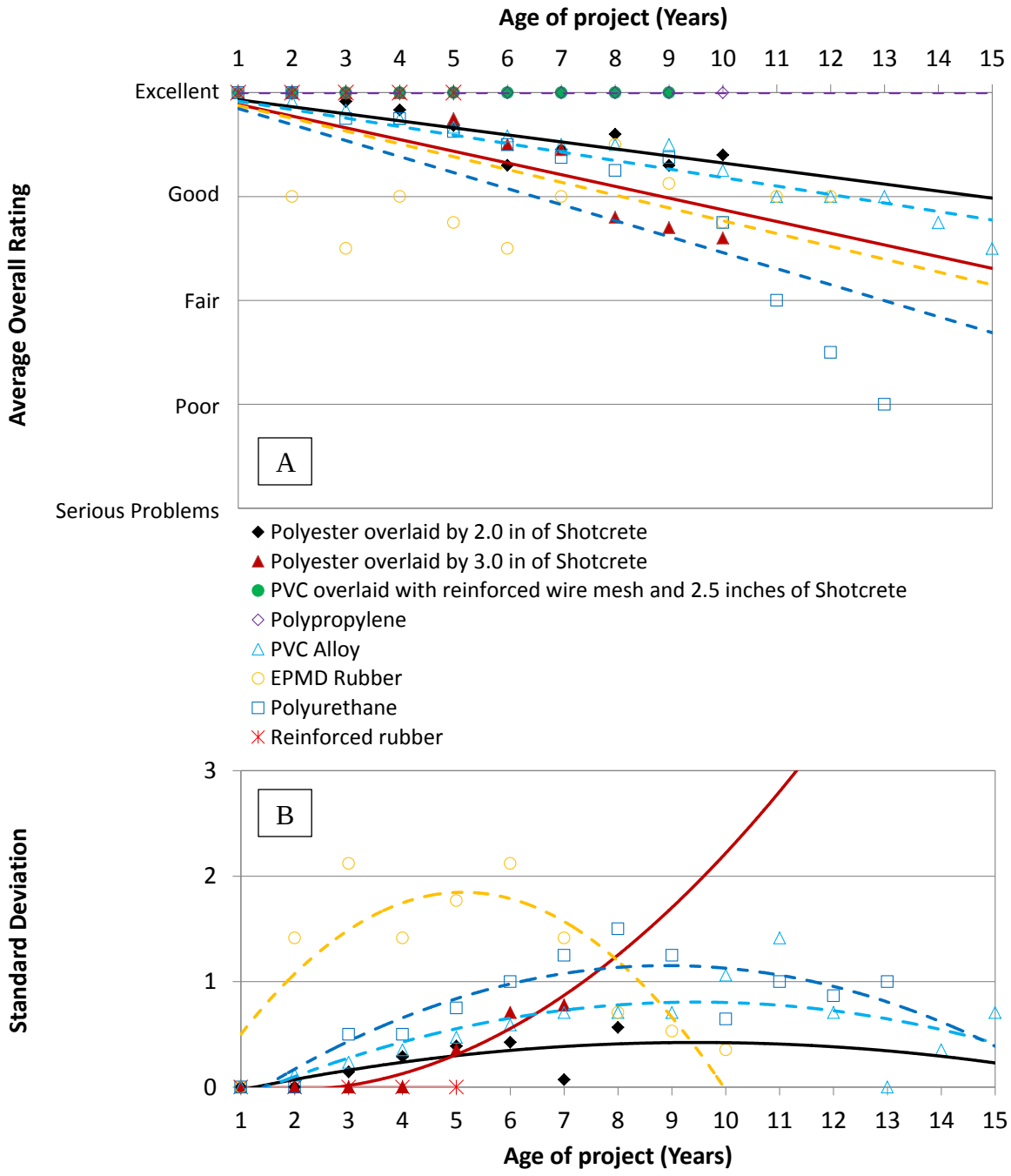

Figure 9. Yearly performance by liner material and regression analysis, for project not affected by poor installation and vandalism. A) Average; B) Standard Deviation

Liners with a Protective Barrier

All six (6) projects are still in Good or Excellent condition after 5 to 10 years and have required little maintenance. No difference in performance was observed between the two types of synthetic liners used under the shotcrete. Water infiltrating behind the liner where not properly anchored has resulted in buckles (Fig. 10). Most buckles were found in the eastern section of Project No.5. Although we did not find any evidence of damages on the synthetic liner underneath buckles, more data should be collect on this regard. Other observed damages are erosion under the synthetic liner caused by insufficient free-board, and horizontal cracks found especially close to work zones. Figure 11 shows horizontal cracking likely caused by the heavy machines working next to the southern bank of project No. 5.

Figure 10. A buckle on the shotcrete protective barrier overlaid on polyester (Project No.5)

Figure 11. Horizontal hairline crack on the shotcrete protective barrier, likely caused by heavy machines working next to the southern bank of Project No. 5

Liners without a Protective Barrier

The performance of the liners without a protective barrier has varied significantly. All projects with reinforced rubber were rated as *Excellent*, but have only been in place for five (5) years. Of the other four types of materials, the polypropylene and PVC alloy liners had the least amount of damage, although polypropylene has only two (2) projects, one rated *Excellent* and one rated *Serious Problems*. The performance of EPDM rubber and polyurethane varied significantly, and rating ranges from *Good* to *Serious Problems* with many projects being completely removed.

Exposed liners are more susceptible to damage caused by weather, animals, farm machinery traffic, and vandalism (even if unintentional such as fishing in the canal). As a result, liners in remote areas have performed much better than those in urban or high traffic areas. Damage was also caused by districts' maintenance activities, such as mowing and cleaning out of aquatic vegetation and sedimentation (Fig. 12). Furthermore, installation procedures and the smoothness and stability of the material underneath the liner resulted critical factors affecting materials performances.

Figure 12. Damage on the anchor likely caused by district mowers.

Polypropylene

The two polypropylene projects are rated as *Excellent* and *Serious Problems*. Project No.4 is in *Excellent* condition after ten (10) years, with no visual problems, except for the last few linear feet where the concrete canal section has collapsed. Project No.9 (9-years old) was rated as *Serious Problems* due to extensive damage caused by collapsing wall, very sharp-edged canal concrete sections, and vandalism (Fig. 13 and 14). Damaged parts of this project were removed, and the rest is still in good conditions (Fig. 15)

Figure 13. Collapsing and very sharp-edged canal concrete sections (Project No. 9)

Figure 14. Damage caused by vandalism (Project No. 9)

Figure 15. Portion of Project No. 9 in good conditions

PVC Alloy

Of the three (3) 15-years old PVC Alloy projects, one was rated *Good* (No. 22), one *Fair* (No.16) and one *Serious Problems* (No.24). This material has shrinking problems but is pretty resistant, and tears do not expand easily (Fig. 16). Performance was therefore overall good, excluding Project No.24 were extensive damage has occurred due to nearby road construction activity. We noticed some new scattered natural degradation of the material, which should probably be repaired and monitored to prevent more serious damage.

Figure 16. Damage caused by maintenance (Project No. 22)

EPDM Rubber

Of the nine (9) EPDM projects, only one sub-project (No. 7E) is still in *Good* conditions after ten (10) years, while the ratings of the others range from *Fair* to *Serious Problems*. Intensive maintenance was required with this material, and several projects (No. 8, 12, 14, 19 and 26) and several sections from other projects have been removed. All the oldest projects (14 years of age) have *Serious Problems*.

EPDM rubber is a soft material very susceptible to vandalism and punctures caused by animals, including ants, and easily damaged by district maintenance operations. Children are reported to cutoff portions of the liner for use as rubber bands. Unless repaired in a timely manner, these tears quickly enlarge. Shrinking is also a serious problem, and caused enlargement of cuts, seams opening and detachment from canal walls (Fig. 17 and 18.) Serious damages were caused also by water infiltrating from above the anchor and uneven material underneath the liner (Fig. 19 and 20.) Therefore, proper installation of this type of liner is critical.

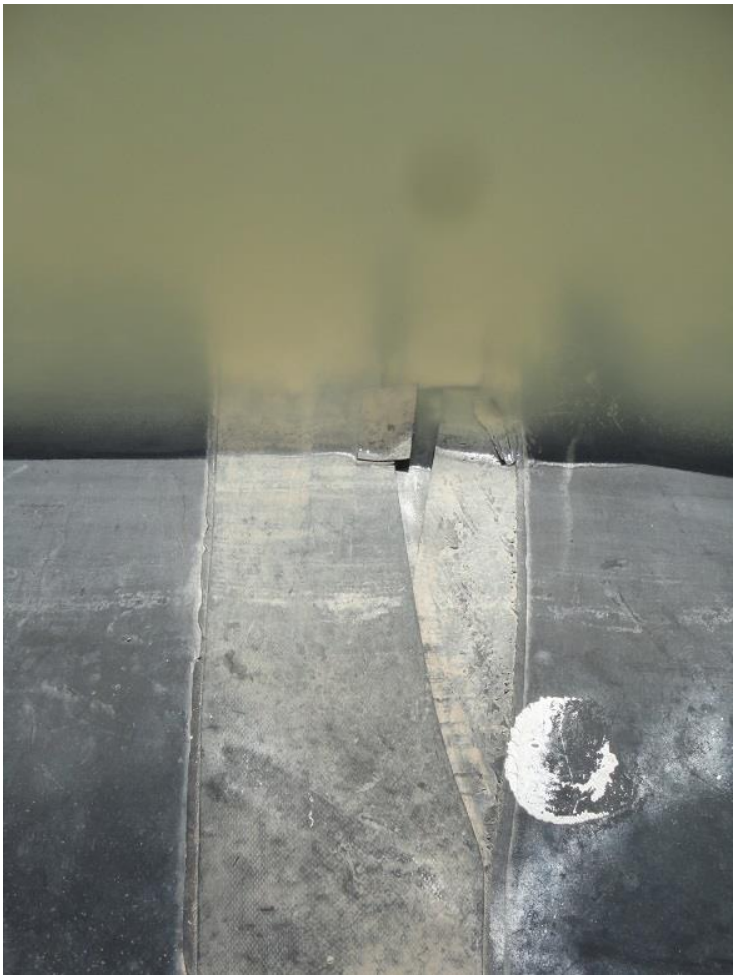

Figure 17. Shrinking of the rubber causing a seam to open (Project No. 7)

Figure 18. Large spacing between liner and canal sides due to shrinking of rubber, visible through a large cut (Project No. 13)

Figure 19. Water level above anchor (Project No. 7)

Figure 20. Uneven material underneath the liner in the anchor of a removed section (Project No. 7)

Polyurethane

Of the nine (9) polyurethane projects, only one (1) is rated as *Fair* after 10 years (No.6). The others are fifteen (15) years old, and all have *Serious Problems*. Five (5) projects have been removed (No. 11, 17, 18, 20, 21). Unlike other types of liners, the polyurethane was manufactured on-site by specialized machinery, and requires that the chemicals used to be properly handled. Several problems occurred during its manufacture and installation, including inconsistency in product thickness. Some maintenance was carried out where damage was not too large.

We found many cuts and holes, and large portions collapsed because of sharp edges of anchor, farm and district traffic, and inconsistency of product thickness (Fig. 21 and 22). In some segments the top layer of the material has only peeled off, or damage is limited to the anchor, with a minor effect on performance (Fig. 23).

Figure 21. Damage caused by the sharp edge of concrete underneath the liner

Figure 22. Polyurethane liner hanging off the canal side

Figure 23. Polyurethane liner peeling off in the anchor

Reinforced rubber (collaboration with Firestone)

All three projects that were donated by Firestone Inc. to improve their rubber products poor performances have been rated *Excellent* (Fig. 24). Out of all tested products, this is the only one that has shown no decline in average performances at the fifth (5^{th}) year of testing. The material underneath looks even and smooth, there is no significant shrinking, and vandalism is not a problem in this area.

Figure 24. Reinforced FPP-R in excellent condition after 5 years

Multi-layer Polyethylene

In 2012 HCID1 installed a new material (Multi-layer Polyethylene) in place of some Polyurethane and EPDM Rubber projects that were removed. The main advantage of this material is that is difficult to tear after cut, and therefore is less affected by vandalism, and that is easy to install. Ratings in 2013 ranged from *Good* to *Excellent*. Some damage was found on the anchor, which was caused by sharp edges of the concrete underneath the liner, and district mowers (Fig. 25). Additionally, some little holes might have been caused by ants. No damage has extended to the canal wetted area.

Figure 25. Multi-layer Polyethylene cut due to sharp and collapsing anchor

SUMMARY OF FIELD RATING RESULTS

The six (6) projects with a protective barrier were rated from *Excellent* to *Good* after 5-10 years. The use of a protective barrier can extend the life of the lining project by preventing inadvertent damage and discouraging vandalism. Our main concern is the long term impact of buckles on the synthetic liner's underneath.

The performance of the synthetic liners without a protective barrier varied dramatically, ranging from *Excellent* to *Serious Problems*. Some were found to be more susceptible to such factors as installation problems, unintentional damage caused by canal maintenance, and vandalism. Among the installation issues the most important is the smoothness and stability of the material underneath the liner, and the shrinking properties. Most of the damage to the synthetic liners occurred around the exposed areas of the liner near the top anchor area.

Key observations for each type of liner are as follow:

- PVC and Polyester with a shotcrete protection barrier
    - Of the six (6) projects, four (4) are still in *Excellent* conditions after 5 to 9 years of age, and two (2) are in *Good* condition after 10 years
    - Typically, damages are buckles caused by wall structural problems and water infiltrating behind a liner not properly anchored, and horizontal and pencil size cracks in the shotcrete found especially close to work zones
    - PVC with protective barrier performed slightly better compared to Polyester with protective barrier
    - Little maintenance has been required to-date

- Polypropylene
    - One project was rated as *Excellent* after ten (10) years, while the other had *Serious Problems* after nine (9) years and had some sections removed
    - Cuts and collapsing liner are the typical damages, and were caused by vandalism, wall structural problems, and sharp concrete edges in the anchor
    - Little maintenance has been required to-date

- PVC Alloy
    - Of the three (3) 15-years old projects, one was rated *Good*, one *Fair*, and one *Serious Problems*.
    - We found small cuts and tears, likely resulting from district mowers and shrinkage of the product; big cuts in one short segment were caused by road works
    - Some very small degradation holes were probably caused by weather
    - Little maintenance has been required to-date

- EPDM Rubber

    - Of the nine (9) projects, only one sub-project is still in *Good* conditions after ten (10) years, while the ratings of the others range from *Fair* to *Serious Problems.* All the oldest projects (14 years of age) have *Serious Problems*. Five (5) projects and several sections from other projects have been removed
    - Is an easy to cut material due to its softness
    - We found many holes and cuts, caused by sharp edges of canal, uneven material underneath, traffic (animals, farm and district machines), vandalism (children cutting portions of it to play); cuts enlarged easily when not repaired, mainly because of shrinking
    - Material detached from the canal walls, because of shrinking and water infiltrating behind the liner
    - Constant maintenance has been required

- Polyurethane

    - Of the nine (9) projects, only one (1) is rated as *Fair* after 10 years. The others are fifteen (15) years old, and all have *Serious Problems*. Five (5) projects have been removed
    - We found many cuts and holes, and large portions collapsed because of sharp edges of anchor, farm and district traffic, and inconsistency of product thickness (material is produced and installed on the site)
    - The material has two (2) layers glued together. While the top layer had soon serious damage (pealing and degradation), the bottom layer has resisted longer
    - Some maintenance was carried out where damage was not too large

- Reinforced Rubber (collaboration with Firestone)

    - All three (3) projects have been rated *Excellent*, and are all five (5) years of age
    - The material was installed to evaluate a more resistant rubber compared to previous tests
    - No damages were found so far, also because of the location and good installation practices (no vandalism, smooth material underneath, not tight installation)

- Multi-layer Polyethylene

    - Of these projects installed in 2012, one (1) has been rated *Excellent,* and two (2) have been rated *Good*
    - The material was installed to evaluate a material easier to install and difficult to tear compared to previous tests
    - We found few cuts caused by mowers and wall structural problems, but they did not expand to the wet area, and can be patched if needed

A summary of factors affecting materials performances, and observed consequences are reported in table A- 6

ACKNOWLEGDEMENTS

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The districts involved in this project provided assistance through their canal riders and personnel supervisors, which resulted useful for the identification of the causes of damage.

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APPENDIX: Detailed Tables

Table A- 1. Location, Type, Extent, and date of installation of Lining Project in Eight Districts

Irrigation District	Project	Canal	Material	Total Length		Date of Installation
				Feet	Miles	
CCID No.2	1	Canal C	Polyester overlaid by 2.0 inches of shotcrete	18,323	3.47	Jan-Nov 2004
	2	Canal 39	PVC overlaid with reinforced wire mesh and 2.5 inches of shotcrete	13,851	2.62	Jan 2005
	3	Canal 13	Polyester overlaid by 2.0 inches of shotcrete	21,304	4.03	Sept 2006-Jan 2007
Santa Cruz	4	Main Canal	Polypropylene	1,836	0.35	Nov 2004
HCID No.2	5	Lateral A	Polyester overlaid by 3.0 inches of shotcrete	38,282	7.25	Sept 2004
Harlingen	6	Wyrick Canal	Polyurethane	960	0.18	Nov 2004
	7	Wyrick Canal	EPDM Rubber	11,987	2.27	Nov 2004
United	8	Mission Main	EPDM Rubber	666	0.13	Feb 2005
Delta Lake	9	Raymondville Canal	Polypropylene	1,334	0.25	Dec 2005
Maverick	28	Lateral 2a	EPMD Rubber	9,587	1.82	2004
Adams Garden	30	AG 15	Reinforced EPDM	92	0.02	2009
Adams Garden	31	AG 15	Reinforced FPP-R	207	0.04	2009
Adams Garden	32	AG 15	Green TPO-R	305	0.06	2009
United	33	Bryan Canal	Polyester Overlaid by 2.0 inches of Shotcrete	1,396	0.26	2009

Table A- 2. Location, Type, Extent, and date of installation of Lining Project in HCID No.1

Project	Canal	Material	Total Length		Date of Installation
			Feet	Miles	
10	East Main Canal	Polyurethane	1,812	0.34	1999
11	East Main Canal	Polyurethane	1,356	0.26	1999
12	East Main Canal	EPMD Rubber	994	0.19	2000
13	East Main Canal	EPMD Rubber	1,283	0.24	2000
14 (36)#	East Main Canal	EPMD Rubber (Multi-layer Polyethylene)	190 (900)	0.04 (0.17)	2000 (2012)
15	East Main Canal	Polyester overlaid by 3.0 inches of shotcrete	109	0.02	2007
16	East Main Canal	PVC Alloy	23	0.004	1999
17 (35)##	East Main Canal	Polyurethane (Multi-layer Polyethylene)	600 (1,335)	0.11 (0.25)	1999 (2012)
18 (35)	East Main Canal	Polyurethane (Multi-layer Polyethylene)	305	0.06	1999 (2012)
19 (35)	East Main Canal	EPMD Rubber (Multi-layer Polyethylene)	161	0.03	2000 (2012)
20 (35)	East Main Canal	Polyurethane (Multi-layer Polyethylene)	223	0.04	1999 (2012)
21 (35)	East Main Canal	Polyurethane (Multi-layer Polyethylene)	46	0.01	1999 (2012)
22	East Main Canal	PVC Alloy	46	0.01	1999
23	East Main Canal	Polyurethane	555	0.11	1999
24	East Main Canal	PVC Alloy	17	0.003	1999
25*	East Main Canal	Polyurethane	651	0.12	1999
25** (34)	East Main Canal	Polyurethane (Multi-layer Polyethylene, part)	622	0.12	1999 (2012)
26	Lateral 19	EPMD Rubber	200	0.04	2000
27	Lateral 19	EPMD Rubber	1,339	0.25	2000

New Project No. 36 replaces old project No. 14, and extends further

New Project No. 35 replaces old projects No. 17-21; total length is reported in this line

* Remaining part after removal and replacement with new material (project No. 34)

** Part removed and replaced with new material (project No. 34)

Table A- 3. Performance Rating by Project for the entire period of study

Project No.	Material Type	2005	2006	2007	2009	2011	2013
1+	Polyester overlaid by 2.0 inches of shotcrete	Excellent	Excellent	Excellent		Good	Good
3				Excellent		Good	Excellent
33					Excellent	Excellent	Excellent
5+	Polyester overlaid by 3.0 inches of shotcrete	Excellent	Excellent	Excellent	Good	Good	Good
15				Excellent	Excellent	Excellent	Excellent
2+	PVC overlaid with reinforced wire mesh and 2.5 inches of shotcrete	Excellent	Excellent	Excellent		Excellent	Excellent
4	Polypropylene	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
9		Excellent	Excellent	Excellent		Serious Problems	Serious Problems
16	PVC Alloy	Excellent	Excellent	Excellent	Excellent	Good	Fair
22		Good	Good	Good	Fair	Good	Good
24		Good	Good	Good	Poor	Serious Problems	Serious Problems
7+	EPMD Rubber	Fair	Poor	Fair	Poor	Poor	Poor
8		Excellent	Poor	Fair	Good	Poor	Serious Problems
12		Good	Fair	Fair	Poor	Serious Problems	Serious Problems
13*		Good	Fair	Good	Fair	Serious Problems	Serious Problems
14		Good	Fair	Removed			
19		Excellent	Excellent	Excellent	Good	Good	Removed
26		Good	Fair	Serious Problems	Removed		
27		Good	Fair	Serious Problems	Serious Problems	Serious Problems	Serious Problems
28					Serious Problems	Serious Problems	Serious Problems

* Only 13a (13b was removed and replaced probably in 2010)
+ Project was split in sub-projects

(Table A-3 continue)

Project No.	Material Type	2005	2006	2007	2009	2011	2013
6	Polyurethane	Excellent	Good	Good	Fair	Poor	Fair
10		Good	Fair	Fair	Poor	Serious Problems	Serious Problems
11		Poor	Serious Problems	Removed			
17		Excellent	Excellent	Excellent	Fair	Fair	Removed
18**		Excellent	Excellent	Excellent	Poor	Serious Problems	Removed
20		Serious Problems	Serious Problems	Serious Problems	Serious Problems	Serious Problems	Removed
21		Excellent	Excellent	Excellent	Good	Poor	Removed
23		Good	Good	Good	Fair	Poor	Serious Problems
25		Excellent	Good	Good	Serious Problems	Serious Problems	Serious Problems
30	Reinforced EPDM				Excellent	Excellent	Excellent
31	Reinforced FPP-R				Excellent	Excellent	Excellent
32	Green TPO-R				Excellent	Excellent	Excellent
34	Multi-layer Polyethylene						Good
35							Good
36							Excellent

** Only 18a (18b was removed and replaced in 2008)

Table A- 4. Performance Rating by Sub-Project in 2011 and 2013

Project No.	Material Type	Feet	Miles	2011	2013
7A	EPMD Rubber	1,069	0.20	Serious Problems	Removed
7B		3,463	0.66	Serious Problems	Serious Problems
7C		1,961	0.37	Serious Problems	Serious Problems
7D		2,809	0.53	Poor	Fair
7E		1,336	0.25	Good	Good
7F		1,350	0.26	Good	Fair
13A	EPMD Rubber	248	0.05	Serious Problems	Serious Problems
13B*		1,035	0.20	Fair	Serious Problems
1A	Polyester overlaid by 2.0 inches of shotcrete	2,614	0.50	Good	Good
1B		9,187	1.74	Good	Good
1C		3,920	0.74	Good	Good
1D		1,303	0.25	Excellent	Excellent
1E		1,300	0.25	Good	Excellent
5A	Polyester overlaid by 3.0 inches of shotcrete	2,678	0.51	Excellent	Excellent
5B		3,148	0.60	Excellent	Good
5C		2,970	0.56	Good	Good
5D		3,828	0.73	Excellent	Good
5E		5,543	1.05	Fair	Fair
5F		3,101	0.59	Fair	Fair
5G		3,151	0.60	Fair	Fair
5H		1,528	0.29	Excellent	Good
5I		9,989	1.89	Poor	Fair
5L		2,345	0.44	Fair	Fair
18A	Polyurethane	203	0.04	Serious Problems	Removed
18B**		102	0.02	Good	Removed
2A	PVC overlaid with reinforced wire mesh and 2.5 inches of shotcrete	8,014	1.52	Excellent	Excellent
2B		5,837	1.11	Excellent	Excellent

* The original liner has been removed and replaced probably in 2010

** The original liner has been removed and replaced in 2008

Table A- 5. Calculation of average rating (Av) and standard deviation (Std) based on the age of the project
(1=Excellent, 2=Good, 3=Fair, 4=Poor, 5=Serious Problems)

Project / Age	Liners with protective barrier											Liners without protective barrier								
	Polyester Overlaid by 2.0 inches of Shotcrete					Polyester overlaid by 3.0 inches of shotcrete				PVC overlaid with reinforced wire mesh and 2.5 inches of shotcrete		Polypropylene				PVC Alloy				
	1	3	33	Av	Std	5	15	Av	Std	2	Av	4	9	Av	Std	16	22	24	Av	Std
1	1.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0	0.0
2	1.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.2	1.2	1.1	0.1
3	1.0	1.3	1.0	1.1	0.1	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.3	1.3	1.2	0.2
4	1.0	1.5	1.0	1.2	0.3	1.0	1.0	1.0	0.0	1.0	1.0	1.0	2.0	1.5	0.7	1.0	1.5	1.5	1.3	0.3
5	1.2	1.8	1.0	1.3	0.4	1.5	1.0	1.3	0.4	1.0	1.0	1.0	3.0	2.0	1.4	1.0	1.7	1.7	1.4	0.4
6	1.4	2.0		1.7	0.4	2.0	1.0	1.5	0.7	1.0	1.0	1.0	4.0	2.5	2.1	1.0	1.8	1.8	1.6	0.5
7	1.6	1.5		1.6	0.1	2.1	1.0	1.6	0.8	1.0	1.0	1.0	5.0	3.0	2.8	1.0	2.0	2.0	1.7	0.6
8	1.8	1.0		1.4	0.6	2.2		2.2		1.0	1.0	1.0	5.0	3.0	2.8	1.0	2.0	2.0	1.7	0.6
9	1.7			1.7		2.3		2.3		1.0	1.0	1.0	5.0	3.0	2.8	1.0	2.0	2.0	1.7	0.6
10	1.6			1.6		2.4		2.4				1.0	5.0	3.0	2.8	1.0	2.5	3.0	2.2	1.0
11																1.0	3.0	4.0	2.7	1.5
12																1.5	2.5	4.5	2.8	1.5
13																2.0	2.0	5.0	3.0	1.7
14																2.5	2.0	5.0	3.2	1.6
15																3.0	2.0	5.0	3.3	1.5

Red values are obtained with linear interpolation (individual projects columns), or are the average of only interpolated data (Av and Std columns)

(Table A- 5 continue)

Project / Age	Liners without protective barrier (cont.)																										
	EPMD Rubber											Polyurethane											Reinforced rubber				
	7	8	12	13a	14	19	26	27	28	Av	Std	6	10	11	17	18a	20	21	23	25	Av	Std	32	30	31	Av	Std
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0	0.0
2	3.0	4.0	1.2	1.2	1.2	1.0	1.2	1.2	1.8	1.8	1.0	1.0	1.2	1.5	1.0	1.0	1.7	1.0	1.2	1.0	1.2	0.3	1.0	1.0	1.0	1.0	0.0
3	4.0	3.0	1.4	1.4	1.4	1.0	1.4	1.4	2.6	2.0	1.0	2.0	1.3	2.0	1.0	1.0	2.3	1.0	1.3	1.0	1.4	0.5	1.0	1.0	1.0	1.0	0.0
4	3.0	2.5	1.6	1.6	1.6	1.0	1.6	1.6	3.4	2.0	0.8	2.0	1.5	2.5	1.0	1.0	3.0	1.0	1.5	1.0	1.6	0.7	1.0	1.0	1.0	1.0	0.0
5	3.5	2.0	1.8	1.8	1.8	1.0	1.8	1.8	4.2	2.2	1.0	2.5	1.7	3.0	1.0	1.0	3.7	1.0	1.7	1.0	1.8	1.0	1.0	1.0	1.0	1.0	0.0
6	4.0	3.0	2.0	2.0	2.0	1.0	2.0	2.0	5.0	2.6	1.2	3.0	1.8	3.5	1.0	1.0	4.3	1.0	1.8	1.0	2.1	1.3					
7	3.9	4.0	3.0	3.0	3.0	1.0	3.0	3.0	5.0	3.2	1.1	3.5	2.0	4.0	1.0	1.0	5.0	1.0	2.0	1.0	2.3	1.5					
8	3.8	4.5	3.0	2.0	5.0	1.0	5.0	5.0	5.0	3.8	1.5	4.0	3.0	5.0	1.0	1.0	5.0	1.0	2.0	2.0	2.7	1.7					
9	3.8	5.0	3.5	2.5	5.0	1.5	5.0	5.0	5.0	4.0	1.3	3.5	3.0	5.0	1.0	1.0	5.0	1.0	2.0	2.0	2.6	1.6					
10	3.8		4.0	3.0	5.0	2.0	5.0	5.0	5.0	4.1	1.1	3.0	3.5	5.0	2.0	2.5	5.0	1.5	2.5	3.5	3.2	1.2					
11			4.5	4.0	5.0	2.0	5.0	5.0		4.3	1.2		4.0	5.0	3.0	4.0	5.0	2.0	3.0	5.0	3.9	1.1					
12			5.0	5.0	5.0	2.0	5.0	5.0		4.5	1.2		4.5	5.0	3.0	4.5	5.0	3.0	3.5	5.0	4.2	0.9					
13			5.0	5.0	5.0	3.5	5.0	5.0		4.8	0.6		5.0	5.0	3.0	5.0	5.0	4.0	4.0	5.0	4.5	0.8					
14			5.0	5.0	5.0	5.0	5.0	5.0		5.0	0.0		5.0	5.0	4.0	5.0	5.0	4.5	4.5	5.0	4.8	0.4					
15													5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	0.0					

Red values are obtained with linear interpolation (individual projects columns), or are the average of only interpolated data (Av and Std columns)

Table A- 6. Summary of factors affecting materials performances, and observed consequences

Type of Liner / Factors	Liners with a protective barrier	Polypropylene	PVC Alloy	EPDM Rubber	Polyurethane	Reinforced Rubber	Multi-layer Polyethylene
Pressure of water infiltrating behind the liner (insufficient free board)	Buckles, Erosion			Detachment from canal			
Wall structural problems	Buckles	Liner collapse					
Sharp edge of canal wall		Cuts		Cuts	Cuts		Cuts
Uneven material underneath liner				Cuts			
Shrinking			Cuts	Detachment from canal, tears enlarging			
Intentional and unintentional vandalism		Holes (children playing)	Tears	Cuts			
Animal traffic				Holes			Holes
Farm and district traffic				Cuts	Cuts		Cuts
Traffic of heavy machinery on embankment	Cracks						
Lack of maintenance				Cut and tears enlarging			
Inconsistency in product thickness					Cuts		
Weather damage			Degra-dation, holes		Degradation, material pealing		