RESISTANCE OF DIGITALLY AND TRADITIONALLY PRINTED MATERIALS TO BLEED, DELAMINATION, GLOSS CHANGE, AND PLANAR DISTORTION DURING FLOOD

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ABSTRACT—It is imperative that cultural heritage institutions with digitally printed materials in their collections understand the sensitivities of these objects to water exposure during flood. Anecdotal evidence from institutions and the general public suggest that some digital print processes are extremely sensitive to water exposure. Understanding this vulnerability will be critical for institutions in modernizing their disaster response plans to include digital prints; inappropriate response could lead to loss of material due to its inherent sensitivity to water or due to contamination of adjacent collection materials through bleeding of the image-forming colorants. A variety of digital print types were immersed in water for 24 hours and then evaluated by measuring changes in color and gloss, and inspecting text readability, delamination, and or planar distortion. As expected, most prints experienced at least slight planar distortion; some, however, suffered extreme forms of damage including colorant bleed or complete delamination or dissolution of the image/text layer. Because the digital prints were often more sensitive than traditional prints to flood damage, results indicate that new flood response strategies should be developed for collections that contain these materials.

TITRE—Résistance des impressions numériques et traditionnelles à la bavure, au délaminage, au changement de brillance et à la déformation pendant les inondations RÉSUMÉ—Il est impératif que les institutions culturelles qui possèdent dans leurs collections des documents imprimés numériquement comprennent la sensibilité à l'eau de ces objets en cas d'inondation. Les données empiriques recueillies auprès des institutions et du grand public semblent indiquer que certains procédés d'impression numériques sont extrêmement sensibles à l'eau. Comprendre cette vulnérabilité constitue une étape importante vers la mise à jour des plans d'intervention après sinistre afin d'y inclure les impressions digitales. Une intervention inadéquate pourrait conduire à la perte de certains documents en raison de leur sensibilité inhérente à l'eau ou bien encore à la contamination d'objets adjacents dans la collection à cause de la bavure des substances colorantes formant les images. Plusieurs types d'impressions numériques ont été immergés dans l'eau pendant 24 heures. Elles ont ensuite été évaluées en mesurant les changements de couleur et de brillance et en inspectant la lisibilité du texte, la délamination des matériaux ou leur déformation. Comme prévu, la plupart des impressions ont souffert au moins une légère déformation planaire; cependant, certaines ont subi des formes extrêmes de détérioration, notamment la bavure des colorants, ou bien la délamination ou la dissolution complète de la couche de texte/image. Les résultats indiquent que les impressions numériques sont souvent plus sensibles à l'eau que les impressions traditionnelles. Pour cette raison, de nouvelles stratégies d'intervention contre les inondations devront être élaborées pour les collections contenant ce type d'objet.

TITULO—Resistencia del material impreso en forma tradicional y digitalmente a que se corran los colores, a la delaminación, a cambios en el brillo y a las distorsiones planares durante una inundación RESUMEN—Es imperativo que las instituciones de patrimonio cultural que tengan material impreso en forma digital en sus acervos entiendan las sensibilidades de estos materiales al ser expuestos al agua durante una inundación. Hay evidencia anecdótica recopilada en estas instituciones y del publico en general que sugiere que algunos procesos de impresión digital son extremadamente sensibles a la exposición al agua. Entender esta vulnerabilidad será de suma importancia para las instituciones para que modernicen sus planes de respuesta ante desastres y que en estos incluyan la impresiones digitales. Una respuesta inadecuada podría conducir a la perdida de material debido a su sensibilidad inherente al agua o causada por la contaminación de colecciones adyacentes al correrse por el agua los tintes y colorantes que forman la imagen. Una variedad de impresiones digitales se sumergieron en agua durante 24 horas y luego se evaluaron midiendo los cambios en color y brillo, se inspeccionó la nitidez de las letras para ser leídas, la delaminación y la distorsión planar. Como se esperaba, la mayoría de la impresiones sufrieron por lo menos de distorsión planar. Sin embargo, algunas sufrieron formas severas de daño incluyendo los colores corridos o delaminación total o disolución de la capa de la imagen o el texto. Ya que las impresiones digitales son frecuentemente mas sensibles a daños durante una inundación que las impresiones tradicionales, se deben desarrollar nuevas estrategias de respuesta para las colecciones que contengan este tipo de material.

TÍTULO—Resistência dos materiais impressos digitalmente ou tradicionalmente impressos ao esborratamento, à delaminação, à alteração de brilho e distorção do suporte à inundação RESUMO—É imperativo que as instituições patrimoniais com materiais impressos digitalmente nas suas coleções percebam a sensibilidade destes objetos em relação à exposição à água durante uma inundação. Evidências anedóticas de instituições e do público em geral sugerem que alguns processos de impressão digitais são extremamente sensíveis à exposição à água. Perceber esta vulnerabilidade será crítico para as instituições na modernização dos seus Planos de Emergência que devem incluir cuidados com as impressões digitais; uma resposta inapropriada pode conduzir à perda de material devido à sua inerente sensibilidade à água ou devido à contaminação dos materiais através do esborratamento dos corantes que formam as imagens de coleções adjacentes. Variados tipos de impressões digitais foram imersos durante 24 horas em água e, em seguida, avaliados através da medição das alterações de cor e brilho, da inspeção da legibilidade do texto, da delaminação e da distorção do suporte. Como esperado, a maior parte das impressões experimentaram, pelo menos, uma ligeira distorção do suporte; algumas, no entanto, sofreram severas formas de danos incluindo o esborratamento dos corantes ou completa delaminação ou dissolução da camada de imagem ou de texto. Porque as impressões digitais são muitas vezes mais sensíveis do que as impressões tradicionais aos danos provocados pelas inundações, os resultados indicam que novas estratégias de resposta às inundações devem ser desenvolvidas para as coleções que contêm este tipo de materiais.

1. INTRODUCTION

The purpose of this project was to determine the relative resistance of various digital print types to bleed, delamination, gloss change, and planar distortion during flood. Experiences of institutions and the general public suggest that some digital print processes are extremely sensitive to water exposure (Burge et al. 2009). What is not clear is how much more sensitive they would be than traditionally printed materials (such as offset lithography and silver-halide color photography) or whether new flood response strategies are needed to properly care for these objects. An understanding of the effects that floods can have on these materials will be a critical aid for institutions creating or modernizing their disaster response plans. Incorrect response during a water disaster could lead to loss of important materials due to inherent sensitivity to water or due to contamination of adjacent materials through colorant bleeding. The data generated by this project will provide collection care staff with a better understanding of how these materials will respond in the unfortunate event of flood.

The term *digital prints* encompasses a variety of printing methods, with the primary digital printing technologies in use today being inkjet, electrophotography (i.e., laser printing), and dye sublimation (technically referred to as dye diffusion thermal transfer or D2T2). Within these, there are some important subcategories. For example, inkjet colorants can be dye or pigment, and inkjet support papers include plain office, fine art, polymer- and porous-photo types. The goal of this project was to characterize the behavior of the various categories and subcategories of materials and not individual products, since institution staff will likely not be able to identify their collection materials to the level of specific printer and paper manufacturers. Below are descriptions of the printing technologies and the types of substrates generally used to create digitally printed photographic images and text-based documents.

1.1 INKJET

Inkjet, a process in which small droplets of ink are rapidly jetted onto the printing paper, is the technology used in many desktop and wide-format printers (and in the near future will be used in digital printing presses to print short-run publications). The technology with the most diverse applications, inkjet printing is used to produce a variety of objects from text-based documents to fine art images. Some inkjet printers are designed to be multi-purpose and print both text and images, while others are specialized for high-quality graphics and photographs.

The primary subcategories of inkjet are dye and pigment. Inkjet dyes have been preferred for some uses because they are less expensive and can produce a greater range of colors, while pigments have been used when resistance to fade is a primary concern. Most inkjet dyes are soluble in water, but inkjet pigments are not. Because of their solubility, inkjet dyes can be prone to bleed at elevated humidity or when contacted by liquid water. (Note: there are some solvent-based inkjet systems; however, these are almost exclusively used in industry for outdoor signage. Only water-based inks were included in this study).

There are also a wide variety of papers that can be used in inkjet printing. Most inkjet documents are printed on plain office papers, but some are created using specialty document papers sometimes called presentation papers. These papers have special coatings that keep the ink close to the surface of the paper, improving color density and line sharpness. Inkjet printed photographs are printed on either a plastic-laminated paper stock (also called resin coated or RC paper) that resembles silver-halide color photo paper, or on fine art paper. The inkjet photo papers can be further segregated into porous and polymer types. The polymer type papers can be printed with dye ink only, while the porous type paper can accept either dye or pigment inks.

The porous type photo papers have a mineral coating with micro- to nano-sized pores that absorb the ink, which dries very quickly after printing. For that reason, porous photo papers are preferred by many users. Unfortunately, because these pores remain open, the colorants are permanently exposed to the air and so are more likely to react with airborne pollutants. The polymer type papers use a swellable coating that absorbs the aqueous ink deep into the polymer. Upon drying, the polymer constricts, enclosing the colorants within the receiver layer, thereby shielding them to some extent from airborne oxidants. Polymer prints are not as highly favored, because they dry slowly and are easy to smear right after printing.

Fine art papers used in inkjet printing resemble watercolor and other traditional art papers. They are selected for their unique tones and textures.

1.2 ELECTROPHOTOGRAPHY

Electrophotography (also referred to as xerography) is used to produce photocopies or prints from laser printers. In electrophotographic systems, light is used to neutralize a charged drum (or belt) in the areas where the image or text is not wanted. The light can come from a laser, LEDs, or can be reflected from the original being copied. Oppositely charged toner particles are then applied to the unexposed (and still charged) areas of the drum. The toner is then transferred from the drum to the paper, and fused by heat and pressure or by evaporation to create the final copy.

Electrophotography can be broken down into dry- and liquid-toner types. The dry-toner types are used for desktop, office, and digital presses, while the liquid-toner type is used only in digital presses. For desktop and office printers, both monochrome (black toner only) and four-color (cyan, magenta, yellow, and black) printers are available. The toners are usually pigments, with the black toner being very stable carbon black. Digital presses are large-scale commercial printers typically found in print shops, and are used for printing short-run publications including single-copy books and photobooks. Desktop and office printers mainly use plain paper for creating documents, but the digital presses can use a variety of substrates including both coated and uncoated paper stocks.

1.3 DYE SUBLIMATION

In dye-sublimation systems, the image-forming colorants are transferred to the print paper from a colored donor ribbon. The printer modulates heat energy to the donor ribbons to control the amounts of yellow, magenta, and cyan dyes that are transferred. This technology is most often used in snapshot-size photo printers and in commercial photo kiosks. Paper choice is very limited with dye-sublimation printers, being restricted to photo type papers. Also, the paper used must typically be made by the same manufacturer of the printer. This process is used only to create pictorial images. It is never used to create documents.

1.4 HISTORY AND SCOPE

Previous experimental work examining the water fastness of digital prints has been performed primarily by manufacturers of the imaging products themselves (Kasahara 1998; Shaw-Klein 1998; Onishi et al. 2001), but also by the Image Permanence Institute (IPI) (Adelstein et al. 2006), and by Jürgens and Schempp (2010). Acknowledging the problem of poor water fastness of some of these materials, in 2005 the major manufacturers of digital print products, working through the International Organization for Standardization (ISO), published a standardized test method by which to evaluate the sensitivities of digital print materials to water (ISO 2005). Jürgens (2009) reported that ad hoc trials during his digital print workshops substantiated the anecdotal reports of digital print water sensitivities. However, at the time of this study, no comprehensive testing of all the primary digital print types (using multiple examples of each technology) was known to have been performed.

A variety of factors influence the extent of damage that collection materials can be expected to experience during a flood. These include the purity of the water (river overflow vs. clean water from a pipe break), the type of enclosures used to house the materials, and whether the prints are kept together in stacks or stored individually. In order to reduce the number of variables, this project deals only with direct exposure of individual digital prints to clear tap water from municipal water systems. Future work may include additional test configurations, such as using dirty or contaminated waters or stacks of prints to further investigate how digitally printed materials will behave in the event of a flood disaster.

2. METHODS

The experimental method used in this study was developed in previous experiments at IPI (Burge and Scott 2010). It was modified from an existing ISO standard (ISO 2005), which had been originally designed for consumer imaging applications and may not match the needs of cultural heritage institutions, in which collection object types may be more diverse (i.e., may include text-based documents) and caretakers may be less tolerant of change. The original ISO method was deemed potentially insufficient for various reasons including the following:

a) The immersion time of one hour was too short.

b) Only pictorial images were included and not text-based documents.

c) The results were reported in just three broad qualitative ratings of "water resistant," "moderately water resistant," and "not water resistant"

The primary changes over the ISO method in this project include extended immersion times, testing both digitally printed photographs and text-based documents, and quantitative measurements.

2.1 TEST SAMPLES

Because of the number of major technology categories, subcategories, and colorant and paper variations involved, a large quantity of different digital print types was required for the experiments. A total of 28 different printer/paper combinations were tested. Of these, 26 were digital prints and 2 were traditional prints. Multiple examples (specific printer/paper combinations) of each printing technology and paper type were tested except for the liquid-toner digital press (only one manufacturer makes this equipment), offset lithography, and color silver-halide photography. Both photo and text-based documents were tested. Table 1 shows each specific printer and paper combination.

As controls for these experiments, two different traditional printing technologies were included: silver-halide type color photographs and offset lithography (table 2). These print types currently exist in collections en masse; collection care personnel are already well acquainted with them and have established best practices for their preservation. Comparing the stability of digital and traditional prints will provide a very important context in which to formulate the much needed collection care practices for the digital prints.

The 26 different digital print types were divided into the major digital printing technologies and their more common subcategories. Table 3 shows the technologies and subcategories under investigation, the primary use of that particular print type (document or photograph), and the total number of printer/paper combinations tested in that category.

Color step wedge, text, and gloss targets along with pictorial images were created for each of the printer/paper combinations. The maximum density cyan, magenta, yellow, and black patches along with an unprinted white area from the color step wedge

Table 1.
Printer and Paper Combinations of Digital Print Test Samples

Technology	Printer	Paper
Inkjet	HP 8250	Harman Matte FB Mp
	Canon ip6600D	Canon Photo Paper Plus Glossy
	Epson R340	Epson Premium Glossy Photo
	HP 8250	HP Premium Plus High Gloss
	Epson R340	Ilford Galerie Classic - Glossy
	Canon ip6600D	Kodak Ultima High Gloss
	Epson 3800	Epson Ultra Premium Presentation
	Canon Pixma Pro9500	Harman Matte FB Mp
	HP B9180	Hahnemuhle Photo Rag Smooth Matte
	Epson C60	Boise X-9 Premium Multipurpose
	Lexmark Z1420	Boise X-9 Premium Multipurpose
	HP Deskjet D4260	Boise X-9 Premium Multipurpose
	Epson CX7400	Boise X-9 Premium Multipurpose
	Lexmark X6570	Boise X-9 Premium Multipurpose
	Kodak Easyshare 5300	Boise X-9 Premium Multipurpose
Dye sublimation	Sony DPP-FP35	SVM-F120P for DPP-F Series
	Canon Selphy ES-1	Canon E-P100 for Canon Selphy ES
Electrophotography	HP Laserjet 2420	Boise X-9 Premium Multipurpose
	Brother HL-5240	Boise X-9 Premium Multipurpose
	Samsung ML-2510	Boise X-9 Premium Multipurpose
	Xerox Phaser 6250	Boise X-9 Premium Multipurpose
	Lexmark C500N	Boise X-9 Premium Multipurpose
	HP Laserjet 1600	Boise X-9 Premium Multipurpose
	Xerox iGen 4	Sterling 80# Gloss Text
	Kodak Nexpress NP2100	Utopia Digital U2 Gloss 80# Text
	HP Indigo 5500	Utopia Digital U2 Gloss 80# Text

were used to monitor changes in color that may result from colorant bleed, either loss of colorant from the dark areas of the print or deposit of bled colorant onto the white areas of the print. The text target contained lines of text ranging in size from 8 to 14 points in Times New Roman font. The text target was used to determine how flood may affect text readability. The top half of the text target included black text on a white background, whereas the bottom half had white text on a black background. While the majority of documents are black text on a white field, for some graphic objects (e.g., posters, brochures), text can be white on a black field. The gloss target was a 7.6 × 7.6 cm (3 × 3 in.) sheet with no image. For most of the gloss targets, unprinted paper was used; however, the dye-sublimation paper was printed to minimum density (Dmin) so as to include the protective overcoat, and the silver-halide color photo paper was unexposed and processed to Dmin. Lastly, pictorial images were included for the visual assessments.

The test targets were printed in triplicate for each printer/paper combination; two of each target were tested and one was stored in a foil-laminated, sealed bag in the dark, as a control. All of the prints were created using printer settings that matched the paper type (e.g., plain or photo), as this would ultimately affect the total quantity and ratios of colorant mixtures throughout an image's tonal range as well as across the various image colors. Failure to use correct printer settings can result in ink over- or

Table 2.
Printer and Paper Combinations of Traditional Print Test Samples

Technology	Printer	Paper
Silver-halide color photo	Photo Lab	Kodak Royal Digital Paper
Offset lithography	Heidelberg Speedmaster	Hansol Titan Gloss 80# Text

Table 3. List of Test Materials Categories

Printing Technology	Paper Type	Primary Use	No. of Examples
Dye inkjet	Porous-coated photo	Photo	3
Dye inkjet	Polymer-coated photo	Photo	3
Dye inkjet	Plain paper	Document	3
Pigment inkjet	Fine art photo	Photo	3
Pigment inkjet	Plain paper	Document	3
Dye sublimation	Dye sublimation	Photo	2
B&W electrophotography	Plain paper	Document	3
Color electrophotography	Plain paper	Document	3
Digital press (dry toner)	Coated glossy	Document	2
Digital press (liquid toner)	Coated glossy	Document	1
Silver-halide color photo	Chromogenic	Photo	1
Offset lithography	Coated glossy	Document	1

under-loading at the paper surface. After printing, all samples were dried in the dark at 21°C and 50%RH for 2 weeks before testing.

2.2 WATER IMMERSIONS

Prints were immersed in separate water baths to prevent colorant bleed between samples. Tap water at 21°C was used for each test. All prints were kept face down, and a wire mesh was used to hold the sheet fully underwater if it would not stay submerged on its own. The assessment of whether a paper would float or sink was made immediately after the sample was submerged and verified several minutes later.

The materials were immersed for 24 hours. Continuous agitation was not used during the soak in order to prevent the additional stresses and variability of water flow; however, the samples were agitated gently for the last 10 seconds to rinse any bled colorants from the prints' surfaces.

At the end of the immersion, the samples were removed from the water bath and set out horizontally, face up, on blotter paper to air-dry. Applying blotter paper to the surface of the prints has been suggested as a method for accelerating drying; however, preliminary tests conducted at IPI have shown that certain print types may stick to blotter paper, so this was not done. The prints were dried for a minimum of 48 hours. After completely drying, the prints were flattened between sheets of blotter paper for one week with two 20.3 × 25.4 cm (8 × 10 in.) sheets of 0.6 cm (¼ in.) glass placed on top. The flattening was performed in order to facilitate data collection by the measurement devices. The samples were not pre-exposed to high humidity to aid flattening, as some of the colorants could be sensitive to additional bleed under those conditions, potentially confounding the flood results.

2.3 EVALUATIONS

Four types of evaluations were performed for this test: visual, colorimetric, text readability, and gloss.

After drying, the pictorial image targets were visually examined for damage. To avoid observer-to-observer variability, one individual completed the visual assessment for the following types of damage:

- Colorant bleed: migration of colorant (pigment, dye, or toner) to other areas of the print or into the test water

- Delamination/Dissolution: peeling (in part or in entirety) or dissolution of the image-receiving and/or image-bearing layer of a print
- Planar distortion: curl or cockling of the paper

A Gretag-Macbeth Spectrolino/Spectroscan spectrophotometer (D50 light source, 2° observer, and no UV cut-off filter) was used to measure the CIELAB values of the color step wedge targets both before and after the flood test, and ΔE was then calculated. A measure of color change, ΔE incorporates changes in lightness as well as hue in a single value. Increases in ΔE indicate increases in color change.

The text targets were examined visually to determine the smallest readable point size (between 8 and 14) after the flood test. This was done for the black text on white background and for the white text on black background.

A BYK Gardner micro-TRI-gloss meter was used to measure the gloss values. This device measures gloss using three different angles of incident light. Glossy surfaces are best measured at 20°, semi-gloss surfaces at 60°, and matte surfaces at 85°. Three measurements were taken on each sample before and after flood simulation to determine the average change in gloss.

3. RESULTS

The damages that occurred to the samples as a result of the flood experiment varied not only from technology to technology, but also from product to product within each technology. For example, one dye sublimation product remained intact after immersion, while another was destroyed when its image layer completely delaminated from its paper support. The original design of the method called for averaging the results of all products within a given technology (such as dye inkjet), however, due to this variability, using averages may cause some technologies to appear resistant when in fact one of the products tested was irretrievably damaged by flood and the others barely affected. Averaging two good materials and one bad material could lead to the erroneous conclusion that all prints created by the particular technology would be somewhat flood resistant. Additionally, it will usually not be possible for collection care personnel to identify print types to the level of specific printer and paper products, so reporting results of specific products would not be a tenable solution either. Therefore, instead of averaging the results, the results of the worst-case example are reported for each printing technology. This approach will lead to the most conservative recommendations for protecting digitally printed materials (and potentially any adjacent materials) from harm during floods.

3.1 VISUAL RESULTS

Table 4 shows the criteria for the number ratings (0 to 3) used to visually assess each print's condition after flood for each of the following parameters: color bleed, delamination or dissolution, and planar distortion. Table 5 shows the visual assessments of the most damaged print for each technology.

The dye inkjet prints bled the most whether they were on polymer-coated or plain papers. The image-receiving layer, image-bearing layer, or colorants of some of the polymer-coated inkjet, dye sublimation, and liquid-toner digital press prints delaminated or dissolved, but not all of the products tested within each of those technologies exhibited the problem. The dry-toner digital press, offset lithography, and silver-halide color photo printing technologies all showed minor problems with blistering. Blistering, however, could be a precursor to total delamination. This may mean that immersion times during floods that exceed 24 hours could exacerbate the problem and lead to total loss of the print.

In addition to the colorant bleed, delamination, and dissolution problems, nearly all the samples exhibited some level of planar distortion. The samples on plain papers tended to distort more than those on photo papers. It may be possible to treat these prints to remove or reduce the planar distortions; however, treatments that involve the application of heat could be problematic, as some digital print types such as electrophotography and dye sublimation may be sensitive to elevated temperatures (Paschke 2002a, 2002b). Treatment with elevated humidity can also lead to additional dye bleed in some inkjet prints (Salesin et al. 2010). None of the prints distorted to the point where the image or text was unreadable (curled or folded over on itself), so a rating of three for this category may be unnecessary in future tests.

None of the digital prints were more resistant to colorant bleed, delamination, dissolution, blistering, or planar distortion than traditionally printed

Table 4.
Visual Assessment Rating Criteria

Rating	Color Bleed	Delamination/Dissolution	Planar Distortion
0	No change	No change	No change
1	Very slight bleed at image edges	Slight delamination around print edges	Slight curl or cockling
2	Clearly noticeable bleed, image/text still discernible/ readable	Delamination around print edges, blistering of image layer	Significant cockling, image/text still discernible/readable
3	Image/text indiscernible/ unreadable	Image/text completely delaminated or dissolved	Image/text indiscernible/unreadable

Table 5.
Visual Assessments

Printing Technology	Paper Type	Color Bleed	Delamination/ Dissolution	Planar Distortion
Dye inkjet	Porous-coated photo	2	0	2
Dye inkjet	Polymer-coated photo	3	3	2
Dye inkjet	Plain paper	3	0	2
Pigment inkjet	Fine art photo	1	0	2
Pigment inkjet	Plain paper	1	0	2
Dye sublimation	Dye sublimation	0	3	1
B&W electrophotography	Plain paper	0	0	2
Color electrophotography	Plain paper	1	0	2
Digital press (dry toner)	Coated glossy	0	2	2
Digital press (liquid toner)	Coated glossy	0	3	2
Silver-halide color photo	Chromogenic	0	2	2
Offset lithography	Coated glossy	0	2	2

materials during flood. Some were equal in their ability to resist damage, but others were clearly more sensitive.

3.2 COLORIMETRIC RESULTS

Table 6 shows the ΔE values for the most damaged print within each technology. Each of the colors was measured at the maximum density in the step wedge. Dmin was measured in an unprinted area.

The ΔE measurements correlated well with the visual results for colorant bleed in table 5. While most of the print types showed little color loss, some were severely damaged by colorant bleed. Two of the three dye inkjet prints on polymer-coated paper were totally destroyed because their ink-receiver coatings dissolved entirely. One of the two dye-sublimation prints was completely destroyed when its ink-receiver layer delaminated entirely from its paper support.

Prints made with dye inkjet consistently showed higher ΔE values than the prints made from all other digital printing technologies. This was true regardless of the paper used. The worst damage was to dye inkjet on polymer-coated photo paper and dye sublimation (which were completely destroyed) followed by dye inkjet on plain document paper. In the case of the plain paper, the image was usually still discernable even with heavy colorant bleed, but the image on the polymer-coated paper was entirely washed away due to dissolution of the image-receiving layer.

The Dmin areas of the prints typically discolored only slightly. The prints that changed the most in the white areas were the same as those with the high ΔE

Table 6.
ΔE Results

Printing Technology	Paper Type	Dmin	Black	Cyan	Magenta	Yellow
Dye inkjet	Porous-coated photo	3	5	6	6	5
Dye inkjet	Polymer-coated photo	*	*	*	*	*
Dye inkjet	Plain paper	6	33	24	68	19
Pigment inkjet	Fine art photo	2	2	2	1	1
Pigment inkjet	Plain paper	3	2	3	3	1
Dye sublimation	Dye sublimation	*	*	*	*	*
B&W electrophotography	Plain paper	1	0	1	1	1
Color electrophotography	Plain paper	2	1	1	2	1
Digital press (dry toner)	Coated glossy	3	0	2	2	2
Digital press (liquid toner)	Coated glossy	2	10	2	3	4
Silver-halide color photo	Chromogenic	1	2	0	4	2
Offset lithography	Coated glossy	2	1	2	2	2

*Too damaged to measure

values for the colors. It is likely that the discolorations of the white areas of these prints were due to colorant bleed and not staining caused by the water itself. If the floodwater had carried colored contaminants (such as dirt) the white areas of all the prints could have been severely discolored. It is important to note that if a print is very prone to colorant bleed; it may also discolor adjacent objects during floods.

Again, none of the digital print types were more resistant to color change during flood than traditionally printed materials. Some were equally sensitive, but others were significantly more sensitive.

3.3 TEXT READABILITY

Table 7 shows the text readability results for the most damaged print for each technology. The numerical rating is the smallest readable point size of the text after flood. When no size was readable, the term “unreadable” was used.

This test has shown that many digitally printed documents, despite being damaged, will still be readable after a flood, even down to an 8-point size font. The results applied to both black text on white background and white text surrounded by a black background. In the latter, the colorants sometimes bled into the white text, rendering it difficult to read, but those samples were still readable at even the smallest font size.

A few samples were even more severely degraded than just by bleed. On the liquid-toner digital press print, the areas of the print containing the largest amount of toner (the white text on a black background) delaminated, while the areas with the least amount of toner (the black text on white paper background) did not. As mentioned previously, two of the three dye inkjet prints on polymer-coated photo paper were completely destroyed, so no text was readable, and one of the dye-sublimation prints had its ink-receiver layer delaminated from the paper support, fully removing all of the text from the paper.

While all the prints from each printing technology were aesthetically damaged by flood in some way (either due to catastrophic damage such as color bleed or delamination, or less severe damage such as gloss change or planar distortion), text in digitally printed documents tended to be more resistant to flood damages than pictorial images. This may be due to the fact that text is usually printed at the highest density possible by the printer. Therefore, more colorant may need to be lost before readability of text is impeded than that needed to be lost in an image which likely has lower densities to begin with. The higher resistance to flood may also be due to the fact that many inkjet printers use pigment for their black color even in systems that use dye for the cyan, magenta, and yellow colors. Since text is typically black and pigment is less sensitive to water, documents may be more resistant to damage during flood. Because of this, documents being preserved for their information content as opposed to artifactual

Table 7. Text Readability – Minimum Readable Font Size

Printing Technology	Paper Type	Black Text/ White Background	White Text/ Black Background
Dye inkjet	Porous-coated photo	8	8
Dye inkjet	Polymer-coated photo	Unreadable	Unreadable
Dye inkjet	Plain paper	8	8
Pigment inkjet	Fine art photo	8	8
Pigment inkjet	Plain paper	8	8
Dye sublimation	Dye sublimation	Unreadable	Unreadable
B&W electrophotography	Plain paper	8	8
Color electrophotography	Plain paper	8	8
Digital press (dry toner)	Coated glossy	8	8
Digital press (liquid toner)	Coated glossy	8	Unreadable
Silver-halide color photo	Chromogenic	8	8
Offset lithography	Coated glossy	8	8

value may be considered more flood resistant than digitally printed photographs.

3.4 GLOSS RESULTS

Table 8 shows the differences in gloss for the most damaged print for each technology. The technologies are ordered according to their initial gloss level.

The matte samples showed no change in gloss. The semi-gloss samples all showed appreciable change in gloss with their specular highlights becoming more diffuse after flood. Changes in gloss did not impede the readability of the information contained in the print whether textual or pictorial, but it did damage the object as an artifact.

For the most part, the digitally printed materials did better than the traditionally printed materials at retaining gloss. The silver-halide color photo paper had the highest initial gloss and showed the greatest gloss difference of all the paper types that were tested. Since silver-halide color photo papers are originally designed to be developed in water-based chemistry and water washed (although they are not meant to be immersed for 24 hour periods), it is surprising that the sample used in this experiment gave such a high gloss difference value. The coated glossy stock for offset lithography was also sensitive to gloss change. The plain paper used in black-and-white electrophotographic prints did not change in gloss at all.

4. CONCLUSIONS

The digitally printed materials were, as a group, more sensitive to bleed, delamination, gloss change, and physical distortion by flood than traditionally printed materials (silver-halide color photo and offset lithography); however, some specific types of digital prints were equally resistant as traditional prints. The digital prints were never more resistant to flood than traditional prints, so each print type may need its own disaster response plan. The damages to the prints varied not only from technology to technology, but were highly variable from product to product within each technology category.

The following digital print types were equally sensitive to flood as traditional prints:

- Pigment inkjet on porous-coated photo paper
- Pigment inkjet on fine art paper
- Pigment inkjet on plain paper
- Color electrophotography
- Digital press – dry toner

The following digital print types were more sensitive to flood than traditional prints:

- Dye inkjet on porous-coated photo paper
- Dye inkjet on polymer-coated photo paper
- Dye inkjet on plain paper
- Dye sublimation
- Digital press – liquid toner

Table 8.
Change in Gloss Units

Printing Technology	**Paper Type**	**Initial Gloss**	**Gloss Difference**
Inkjet and electrophotography	Plain paper	Matte	1
Inkjet	Porous-coated	Matte	0
Inkjet	Fine art photo	Matte	0
Inkjet	Porous-coated	Semi-glossy	11
Digital press (dry toner)	Coated glossy	Semi-glossy	25
Digital press (liquid toner)	Coated glossy	Semi-glossy	19
Offset lithography	Coated gloss	Semi-glossy	21
Inkjet	Polymer-coated	Glossy	*
Dye sublimation	Dye sublimation	Glossy	*
Silver-halide color photo	Chromogenic	Glossy	61

*Too damaged to measure

Some current strategies for dealing with flooded photos allow for materials to be kept in clean water for up to 48 hours before treatment (Heritage Preservation 2005). These results show that such an approach will likely not be appropriate for many digital prints. While dye inkjet on polymer-coated photo or plain office papers will likely be unrecoverable after a flood, previous research has shown that other digital print types may be salvageable if treated early on (Burge and Scott 2010). As such, it is recommended that dye inkjet on porous-coated photo paper, dye sublimation and liquid-toner electrophotography be given priority over traditionally printed materials, pigment inkjet, color electrophotography, and dry-toner digital press. Techniques for drying of materials during salvage will also be critical. An evaluation of potential drying methods was published previously by Jürgens and Schempp (2010).

It is also sometimes recommended that flood damaged photographs be rinsed in clean water before drying (Lavédrine 2003; Heritage Preservation 2005). Care must be taken, understanding the sensitivities to water of the various traditional and digital print types, or this approach could turn a slightly damaged digital print into a total loss.

Because digitally printed materials vary so dramatically in their sensitivities to flood, it will be necessary that collection care personnel be able to accurately identify the various print types. A variety of resources are available to assist in developing this skill including several websites such as www.DP3Project.org and GraphicsAtlas.org, or books such as Jürgens' *The Digital Print: Identification and Preservation* (2009) and Batterham's *The Office Copying Revolution* (2008).

5. RECOMMENDATIONS FOR FUTURE RESEARCH

The ranking of the flood sensitivities of the various materials was a first step towards a more comprehensive understanding of how these materials will behave during flood events. It provides some guidance to collection care personnel regarding how they should respond during such disasters to ensure the survivability of their digital print collections and prevent collateral damage to adjacent collection objects. Work still needs to be done using contaminated floodwater such as found during river overflows, because while flood damage is often due to exposure to clean waters such as during plumbing malfunctions or fire suppression, the worst damage will probably come from weather events or external plumbing failures resulting in unclean floodwaters carrying in dirt and other contaminants from the outside. Work also needs to be done for prints in stacks as well as bound objects, as these too will have unique sensitivities. Finally, post-flood triage, recovery and drying methods, and restorative treatments need to be explored in order to create the most comprehensive disaster plans. While this project provided the first work to quantify and qualify the types and extent of damage to digital prints by flood, there is still much work to do.

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REFERENCES

Adelstein, P., D. Burge, and J. Hanna. 2006. Recovery of water-damaged digital and traditional prints. *Proceedings of the Third International Conference on Preservation and Conservation Issues Related to Digital Printing and Digital Photography*, ed. R. Thompson, A. Manning, and J. Townsend. London: Institute of Physics. 64-67.

Batterham, I. 2008. *The office copying revolution: History, identification, and preservation*. Canberra, Australia: National Archives of Australia.

Burge, D., D. Nishimura, and M. Estrada. 2009. Summary of the DP3 Project survey of digital print experience within libraries, archives, and museums. *Archiving 2009*. Springfield, Va.: Society for Imaging Science and Technology. 133–136.

Burge, D., and J. Scott. 2010. Further studies towards assessing the risk of damage to digital prints during flood events. *Journal of Imaging Science and Technology* 54(2): 020503-1–20503-6.

Heritage Preservation. 2005. *Emergency response and salvage wheel*. Washington, D.C.: Heritage Preservation.

Jürgens, M. 2009. *The digital print: Identification and preservation*. Los Angeles: The Getty Conservation Institute.

Jürgens, M., and N. Schempp. 2010. Freeze-drying wet digital prints: An option for salvage? *Proceedings of the Fourth International Conference on: Preservation and Conservation Issues Related to Digital Printing and Digital Photography*. *Journal of Physics Conference Series* 231(1): 012005

ISO. 2005. Imaging materials: Color images on paper prints, determination of indoor water resistance of printed color images, 18935:2005. Geneva: International Organization for Standardization.

Kasahara, K. 1998. A new quick-drying, high–water-resistant glossy inkjet paper. *NIP 14: International Conference on Digital Printing Technologies*. Springfield, Va.: Society for Imaging Science and Technology. 150–52.

Lavédrine, B. 2003. *A Guide to the Preventative Conservation of Photograph Collections*. Los Angeles: The Getty Conservation Institute.

Onishi, H., M. Hanmura, H. Kanada, and T. Kaieda, 2001. Image permanence of inkjet photographic prints. *NIP 17: International Conference on Digital Printing Technologies*. Springfield, Va.: Society for Imaging Science and Technology. 192–96.

Paschke, C. 2002a. Digital directions part 1: Heat tolerance testing. *Picture Framing Magazine* February 2002: 30–39.

Paschke, C. 2002b. Digital directions part 3: Heat tolerance testing for digital photos. *Picture Framing Magazine* June 2002: 30–36, 100.

Salesin, E., D. Burge, D. Nishimura, and N. Gordeladze, 2010. Short-term high humidity bleed in digital reflection prints. *NIP 26: International Conference on Digital Printing Technologies*. Springfield, Va.: Society for Imaging Science and Technology. 386–89.

Shaw-Klein, L. 1998. Effects of mordant type and placement on inkjet receiver performance. *NIP 14: International Conference on Digital Printing Technologies*. Springfield, Va.: Society for Imaging Science and Technology. 129–32.

SOURCES OF MATERIALS

Author's Note: These materials fall into two classes. The first are commonly available and can easily be found by web search; the second class of materials (especially many printers) are now obsolete and cannot be purchased now, but that is the nature of the digital printing market.

Boise X-9 Premium Multipurpose Paper
Boise, Inc.
1111 West Jefferson St., Ste. 200
Boise ID 83702
(208) 384-7000
www.boiseinc.com

Brother HL-5240 Printer
Brother International
100 Somerset Corporate Blvd.
Bridgewater, NJ 08807-0911
(908) 704-1700
www.brother-usa.com

Canon Selphy ES1 Printer
Canon ip6600D Printer
Canon Pixma Pro9500 Printer
Canon Photo Paper Plus Glossy Paper
Canon E-P100 Paper
Canon USA
One Canon Plaza
Lake Success, NY 11042
(516) 328-5000
www.usa.canon.com

Epson C60 Printer
Epson CX7400 Printer
Epson 3800 Printer
Epson R340 Printer
Epson Premium Glossy Photo Paper
Epson Ultra-Premium Presentation Paper
Epson America
3840 Kilroy Airport Way
Long Beach, CA 90806
(562) 981-3840
www.epson.com

Photo Rag Smooth Matte Paper
Hahnemuhle USA Inc.
722 Calhoun St.
Woodstock, IL 60098
(815) 502-5880
www.hahnemuehle.com

Harman Matte FB Mp Paper
Harman Inkjet Gloss FB AI Paper
Harman Technology Limited
Ilford Way, Mobberley,
Knutsford, Cheshire,
WA16 7JL, England.
+44 (0)1565 684000
www.harmantechnology.com

Heidelberg Speedmaster Sheetfed Press on Hansol Titan Gloss 80# Text Prints
HP Indigo on Utopia Digital U2 Gloss 80# Text Prints
Kodak NexPress on Utopia Digital U2 Gloss 80# Text Prints
RIT Printing Applications Laboratory
66 Lomb Memorial Dr.
Rochester, NY 14623
(585) 475-7090
http://printlab.rit.edu

HP Laserjet 1600 Printer
HP Laserjet 2420dn Printer
HP DeskJet D4260 Printer
HP B9180 Printer
HP 8250 Printer
HP Premium Plus Glossy Paper
Hewlett-Packard Company
3000 Hanover St.
Palo Alto, CA 94304
(650) 857-1501
www.hp.com

Ilford Galerie Classic Glossy Paper
Ilford America Inc.
30 Tower Ln.
Avon, CT 06001
(888) 453-6731
www.ilford.com

Kodak Easyshare 5100 Printer
Kodak Ultima Picture Paper
Eastman Kodak Company
343 State St.
Rochester, NY 14650

(585) 724-4000
www.kodak.com

Kodak Royal Digital Prints
Rowe Photo, Video, Audio
1737 Mt. Hope Ave.
Rochester, NY 14620
(585) 442-8230
www.rowephoto.com

Lexmark X6570 Printer
Lexmark Z1420 Printer
Lexmark C500N Printer
Lexmark International, Inc.
740 W. New Circle Rd.
Lexington, KY 40550
(859) 232-2000
www.lexmark.com

Samsung ML-2510 Printer
Samsung Electronics America
85 Challenger Rd.
Ridgefield Park, NJ 07660
(800) 726-7864
www.samsung.com

Sony DPP-FP35 Printer
Sony SVM-F120P Paper
Sony USA
550 Madison Ave.
New York, NY 10022
(212) 833-8800
www.sony.com

Xerox iGen4 on Sterling 80# Gloss Text Prints
RIT Print/Postal Hub
125 Lomb Memorial Dr.
Rochester, NY 14623
(585) 475-2117
http://finweb.rit.edu/hub/

Xerox Phaser 8560N Printer
Xerox Phaser 6250 Printer
Xerox
45 Glover Ave.
P.O. Box 4505
Norwalk, CT 06856
(203) 968-3000
www.xerox.com

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