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Further Studies Toward Assessing the Risk of Damage to Digital Prints During Flood Events

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Abstract. *This article is intended to provide significant improvements to the existing ISO standardized test method for evaluating the flood resistance of digital prints. The current method, 18935–2005 Imaging materials: Colour images on paper prints: Determination of indoor water resistance of printed colour images, is useful for the evaluation of consumer products but is inadequate for the needs of cultural heritage institutions and the preservation of their collections. These collections contain both pictorial images and documents that are saved for their information content or aesthetic value (or both). Several digital print types were tested with variation in soak time, measurement types, and assessment criteria. The final result of this project is a new test method with expanded evaluation criteria. © 2010 Society for Imaging Science and Technology.*
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INTRODUCTION

The purpose of this article was to examine the ISO test method 18935–2005 *Imaging materials—Colour Images on paper prints—Determination of indoor water resistance of printed colour images*[1] to determine if that method is appropriate to the needs of cultural heritage collections, and if it is not, then to suggest the necessary improvements. The problem is that this standard uses conditions that do not reflect the kinds of conditions often actually experienced in flood events, especially in terms of water exposure duration, water type, and drying. It also uses a simple three-tier evaluation system that does not discriminate between the different types of damage that occur during floods. This article is limited to development of a new test method and does not attempt to rank digital printing technologies or specific products in terms of flood resistance. The audience for these results includes those interested in evaluating digitally printed materials for flood resistance, either for the purpose of product development or product or technology comparisons or for the development of disaster plans for institutional collections of printed material.

REVIEW OF ISO 18935

ISO 18935 consists of three different methods to evaluate print water resistance for both digital and analog prints. Method 1 models the effect of water accidently spilled on a print (such as from a drinking glass) and left to dry. Method 2 is intended to test the physical integrity of the colorant receptive layer when a wet print is dried by blotting or wiping. This is indeed an important feature, as it is possible to have an image that resists bleed when in contact with water but is destroyed if pressure is applied to its surface before it fully dries. Method 3 simulates the behavior of images under catastrophic conditions (e.g., flood). This method uses complete immersion of the print in water and is the method of concern in this project. The method has potential flaws if it is to be used to create data for cultural heritage collections. These are reviewed below.

- The current standard considers only pictorial images; however, digital prints can contain pictures, text, or combinations of the two. Cultural heritage institutions are concerned with all three types. It cannot be assumed that pictorial and text images respond to flood in the same way.
- The ISO test does not differentiate between aesthetic loss and information loss. In many cases the print itself is an artifact of value, especially if it cannot be easily replaced. Even slight changes to objects of artifactual value can severely alter their worth and so must be avoided. On the other hand, some objects have little or no artifactual value but instead have informational value such that retrievability of the information is the primary concern. In this case, readability must survive. As discovered in this project many objects are aesthetically damaged well before their information is compromised.
- The exposure duration in the ISO procedure is limited to 1 h. While this makes the test quick to perform, it does not reflect the longer submersions that prints may endure while flood waters slowly recede or while buildings are being determined safe for reentry by emergency personnel. For this reason a longer test time of 24 h was performed in this article.
- The type of water used in the ISO method is de-ionized or distilled water, which has low ion concentration; it may actually be more aggressive in dissolving print colorants or receiver layers than ordinary tap water, which contains minerals, or river water, which contains a variety of both inorganic and organic components.
- The standard suggests hanging the prints vertically to dry. Since many digital prints are known to bleed it is

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unlikely that institutional staff will hang them. Instead they will dry them flat to minimize the flow of dissolved colorants across the surfaces of the prints.

- Finally, the standard uses only visual assessments of damage. The results are reported in a three-tier system that lumps the variety of possible physical and chemical changes into three broad categories: water resistant, moderately water resistant, and not water resistant. These descriptions are given below:

  (a) *Water resistant:* the print is not noticeably affected by exposure to liquid water and moisture. No significant degradation of the colorant (bleeding, smearing, hue change), of the support (curl, cockle, delamination), or of the image surface (gloss changes, water rings, etc.) is found.

  (b) *Moderately water resistant:* the print exhibits some change or damage by water but is still considered usable for its intended application. The damage can manifest itself as slight media curl, partial delamination along an edge, or ringlike watermarks due to gloss changes or a minor amount of colorant migration. The damage can be mitigated by the rapid removal of the water (careful blotting, shaking off the water, etc.).

  (c) *Not water resistant:* the print is easily damaged by contact with water even when incidental (e.g., a water mist) and is considered unsuitable for applications involving contact with water. Such damage can manifest itself as appreciable curl, delamination of the image layer, colorant bleed into nonimage areas or from color to color or image degradation (hue and gloss changes, surface marks, etc.). It is strongly advisable that users of these materials prevent water contact.

The two extremes of water resistant and not water resistant provide clear indications that, after a flood, a print either will remain intact, retaining all its chemical and physical properties, or will be so thoroughly destroyed that the information contained within the print is irretrievable. The middle category of *moderate water resistance* is very broad and encompasses all types of damage from colorant bleed to gloss change as well as all degrees of damage from slight to severe. While these three categories may be usable for consumer applications, they are not so for cultural heritage institutions, which need a deeper knowledge of the types of damage that can occur. This is necessary in order to take the correct preventative steps before a disaster and to make the right decisions regarding print recovery after a flood.

METHODS

Table I lists the materials that were tested. The prints were chosen to represent not the range of possible digital print types but the range of failure modes and degrees.

The target from the ISO standard was not used, as it was designed solely for visual analysis. For this article, a color step wedge, text (12 pt. Times Roman), pictorial, and D_{min} targets were printed in triplicate for each sample. Two replicates were tested, and one untreated control was retained for comparison purposes. The prints were created using printer settings that matched the paper type (e.g., plain or photo) and object type (text or pictorial image). This would ultimately affect the quantity and ratios of ink mixtures throughout the tonal range and across colors. It was believed that using printer settings that matched paper and object types would provide the best representation of prints in actual collections. For the D_{min} samples, dye sublimation paper was printed to D_{min} so as to include the protective overcoat, and chromogenic paper was unexposed and processed to D_{min}. After printing, all samples were dried and conditioned at 21 °C and 50% RH in the dark for two weeks before testing.

Table I. Test materials.

Printer technology	Colorants	Paper
Dye sublimation	CMY	Dye sublimation
Ink jet dye	CMYK	Plain office
Ink jet pigment	CMYK	Plain office
Ink jet dye	CMYK	Resin-coated porous
Ink jet dye	CcMmYK	Resin-coated polymer
Chromogenic	CMY	Resin-coated polymer

A Gretag Spectrolino/Spectroscan (D50, 2° observer, with no UV cut-off filter) was used to measure the D_{min} patch and the D_{max} patches for the black, cyan, magenta, and yellow colorants both before and after soaking. ΔE was also calculated for ten-step gray scales to evaluate the damage over a variety of tone levels. The D_{min} samples were measured for color change (such as yellowing) using ΔE and OBA loss by monitoring change in reflectance at 440 nm (the peak emission wavelength for the optical brightening agent).

A BYK-Gardner Micro-Tri-Gloss meter, which measures at angles of 20°, 60°, and 85°, was used to measure the change in gloss in the D_{min} samples. D_{min} samples were used to avoid potential confounding from colorant bleed. The optimum angle used for each print is dependent on the initial gloss of the untreated material. Highly reflective surfaces are best measured at 20°, semigloss surfaces at 60°, and matte surfaces at 85°.

Prints were placed in individual water baths to prevent colorant bleed from one sample to another. Tap water at 21 °C was used. Table II lists the substances detected in the local municipal water supply.[2] The prints were immersed facing up if the material tended to sink and facing down if the material tended to float. For materials that tended to float, a wire screen was used to hold the print slightly underwater so that both sides of the print would be exposed to soaking. The assessment of floating or sinking was made initially after the sample was submerged in the water bath and verified several minutes after the start of soaking.

There were two different test periods: 1 and 24 h. Continuous agitation was not used during the soak in order to

Table II. Test water quality.

Substance	mg/L
Barium	0.021
Chloride	26
Fluoride	0.90
Nitrate	0.41
Sodium	13
Sulfate	28
Copper	0.091
Lead	0.005

prevent the additional stresses and variability of water flow; however, the samples were agitated gently for the last 10 s to rinse any bled colorants from the print surfaces.

After immersion, the samples were laid flat to dry on blotter paper on plastic screens. Fans were not used to aid drying to prevent the prints from being blown away. Applying blotter paper to the surface of the prints had been suggested as a method to speed drying; however, certain types of print coatings may exhibit a tendency to stick to the blotter paper, so this was not done. The prints were dried for a minimum of 48 h.

After drying, samples were examined visually for the following changes:

- colorant bleed,
- emulsion dissolution or delamination,
- planar distortion, and
- text readability.

The following scale was used to score the visual damage to the prints:

0 = no change,
1 = slightly noticeable,
2 = clearly noticeable, and
3 = impedes text or image readability.

RESULTS

Visual Assessment of Images

In general, most of the visually assessable damage occurred during the first hour (see Tables III and IV). The ink jet dye image on polymer paper was completely destroyed in the first hour. This was likely caused by both dye bleed and dissolution of the polymer coating.[3] The ink jet dye on plain paper bled, but the image was still identifiable. The ink jet dye on porous paper bled very slightly but only after 24 h. The other print types suffered only planar distortion. The images in these prints remained intact. The most significant damage was due to dye bleed and dissolution of ink receptor layers, while the most common form of damage was planar distortion.

The only difference in the results based on sample soak time was for the ink jet image printed on microporous paper, which showed no change after a 1 h soak time but clearly bled after 24 h. While the bleed did not compromise image information, it did adversely affect the image's aesthetic appeal. For this reason and because many prints in actual floods are immersed for times well beyond the 1 h period used in the existing standard, it is recommended that soak times be extended to 24 h.

Table III. Visual assessment results for 1 h immersion.

Printer	Color bleed	Emulsion loss	Planar distortion
Dye sublimation	0	0	1
Ink jet dye on plain paper	3	0	2
Ink jet pigment on plain paper	0	0	2
Ink jet dye on porous photopaper	0	0	1
Ink jet dye on polymer photopaper	3	3	2
Chromogenic	0	0	1

Table IV. Visual assessment results for 24-h immersion.

Printer	Color bleed	Emulsion loss	Planar distortion
Dye sublimation	0	0	1
Ink jet dye on plain paper	3	0	2
Ink jet pigment on plain paper	0	0	2
Ink jet dye on porous photopaper	2	0	1
Ink jet dye on polymer photopaper	3	3	2
Chromogenic	0	0	2

Table V. Text readability.

Printer	1 h immersion	24 h immersion
Dye sublimation	0	0
Ink jet dye on plain paper	0	0
Ink jet pigment on plain paper	0	0
Ink jet dye on porous photopaper	0	1
Ink jet dye on polymer photopaper	3	3
Chromogenic	0	0

Text Readability

The rating scale used to assess text readability was the same as for visual assessment. Despite other types of damage (gloss change, color shift, and planar distortion) the text was always still readable for all print types, with the exception of ink jet dye on polymer paper (see Table V) which, as stated above, was completely destroyed.

Gloss Results

The values in Tables VI and VII show the change in gloss units due to immersion. The gloss change was severe for many papers. In some cases it was enough to change a print

Table VI. Gloss change results for 1 h immersion.

Printer	Gloss change
Dye sublimation	12
Ink jet dye on plain paper	2
Ink jet pigment on plain paper	2
Ink jet dye on porous photopaper	6
Ink jet dye on polymer photopaper	33
Chromogenic	14

Table VII. Gloss change results for 24 h immersion.

Printer	Gloss change
Dye sublimation	40
Ink jet dye on plain paper	1
Ink jet pigment on plain paper	2
Ink jet dye on porous photopaper	15
Ink jet dye on polymer photopaper	71
Chromogenic	62

Table VIII. Delta E results for 1 h immersion.

Printer	ΔE cyan	ΔE magenta	ΔE yellow	ΔE black
Dye sublimation	0	0	1	0
Ink jet dye on plain paper	30	65	27	3
Ink jet pigment on plain paper	1	1	4	3
Ink jet dye on porous photopaper	5	3	6	2
Ink jet dye on polymer photopaper	Too damaged to read			
Chromogenic	1	0	1	1

Table IX. Delta E results for 24 h immersion.

Printer	ΔE cyan	ΔE magenta	ΔE yellow	ΔE black
Dye sublimation	1	1	1	1
Ink jet dye on plain paper	37	67	58	7
Ink jet pigment on plain paper	1	2	1	1
Ink jet dye on porous photopaper	5	8	4	2
Ink jet dye on polymer photopaper	Too damaged to read			
Chromogenic	1	3	2	1

from glossy to matte. Importantly, while the visual assessment and text readability results changed little from the 1 h immersion to the 24 h immersion, the gloss results for the chromogenic and dye sublimation papers changed dramatically over the same period.

Colorimetric Results

None of the papers showed a ΔE value greater than 1 for the $D_{\min}$ samples, indicating no discoloration of the paper due to flood (in clear tap water). Also, none of the samples showed a significant change in reflectance at 440 nm, indicating no loss of the optical brightening agents.

Tables VIII and IX show the ΔE results for the 1 and 24 h immersions for the $D_{\max}$ patches. In general, the colorimetric results matched the visual assessment results for colorant bleed.

Gray Scale Results

The dye sublimation, chromogenic, and ink jet pigment on plain paper samples all showed very little color change throughout the gray scale (see Figure 1). The ink jet dye on both plain paper and porous paper showed increasing color change from the light through middle tones, then decreasing change from the middle tones through to $D_{\max}$. A possible explanation for this is that as density increases in neutral tones, the pure black ink begins to replace the composite black (C,M,Y mixture). Since the black ink may be made of less soluble colorants, these areas could be more resistant to bleed than the lighter areas. Ink jet photos made with dye-based inks are clearly susceptible to flood damage; however, text documents made with the same printer could be much less so. This is further validated by the text readability data described above.

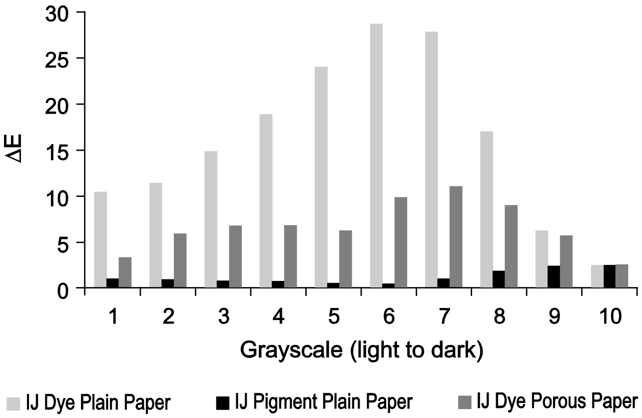

Figure 1. Change in gray scale after 24 h immersion.

This effect also correlates with the ΔE values for the $D_{\max}$ patches shown in Tables VIII and IX. The cyan, magenta, and yellow $D_{\max}$ patches all showed significant color change for the ink jet dye on both plain and porous papers, unlike the black patch, which showed little change. It should therefore not be necessary to measure the entire gray scale to determine if this effect exists for a given print system. If the black $D_{\max}$ shows little change but the other colorants change significantly, it would indicate that text printed with this system should remain readable after flood but that pictorial images would likely be severely damaged.

Ranking of Materials per Parameter

Table X compares the rankings of the materials based on the different assessments: visual, gloss, and ΔE. Text readability

Table X. Rankings by test parameter.

Planar distortion	Gloss change	Color change
IJ dye on porous	IJ pigment on plain	Dye sublimation
Dye sublimation	IJ dye on plain	Chromogenic
Chromogenic	IJ dye on porous	IJ dye on plain
IJ dye on polymer	Dye sublimation	IJ dye on porous
IJ pigment on plain	Chromogenic	IJ pigment on plain
IJ dye on plain	IJ dye on polymer	IJ dye on polymer

was not included, as one sample was completely destroyed and all the others were still readable. Rank order is from best to worst down the column.

Note that there is no consistency in rankings for print materials by test parameter. Each type of damage is thus independent of the others, so each should be measured separately. Of course, not all forms of damage are as offensive as others. For example, changes in gloss may be less disconcerting than dye bleed.

Evaluation

The following table illustrates what the results would be if the three-tiered evaluation method in ISO 18935 (Table XI) were used.

After 24 h of immersion all prints were either moderately resistant or not resistant. The true story is hidden, however. The image layer and dyes of the dye ink jet image on polymer paper were dissolved from the print surface, while the paper support was only mildly cockled. The pigment ink jet image on plain paper remained intact while the paper was severely cockled. Both received the same "not resistant" ranking. For cultural heritage institutions, the first print is completely lost, while the second is potentially repairable by a professional conservator. Therefore, the damage is not truly equivalent. This three-tiered ranking system is inadequate for cultural heritage institutions that will need more specific diagnoses of the damage for the various types of materials in their collections.

Based on the above, the following new test procedure is recommended for assessing the sensitivities of digital print collections in cultural heritage collections during floods.

The following test targets should be used:

- pictorial image for visual assessments;
- $D_{\max}$ patches for each colorant;
- text block containing 12 pt. Times Roman (because it is common); and
- $D_{\min}$ sheets for the $D_{\min}$ ΔE, and gloss meter measurements.

Two replicates of each material should be tested, and one untreated control of each material should be retained for comparison purposes. Printer settings should reflect the type of print being made (text or image) and the type of paper being used. For the $D_{\min}$ samples, dye sublimation paper should be printed to $D_{\min}$ so as to include the protective overcoat, and chromogenic paper should be unexposed and processed to $D_{\min}$. After printing, all samples should be dried and conditioned in the dark to 21°C and 50% RH for two weeks before testing.

The prints should be soaked in tap water at 21°C for 24 h using a wire screen or other suitable holder to keep print immersed. The samples should be agitated for 10 s before removal from the water bath to rinse away any bled colorants from the prints' surfaces. The prints should be air dried horizontally on blotter paper without wiping, blotting, or attempting to accelerate the drying of the prints.

The following scale should be used to score the damage to the prints for each of the visual parameters:

0 = no change,
1 = slightly noticeable,
2 = clearly noticeable, and
3 = impedes text or image readability.

Test results should be reported according to the various parameters. Materials can then be compared by the data for each parameter. A table, such as Table XII below, can be used to compare the data from all the tests.

CONCLUSION

The following conclusion regarding the suitability of using ISO 18935 for cultural heritage collections applications, as well as possible improvements to the test, was drawn.

- 1 h soak time is insufficient. 24 h soak times should be used.

Table XI. ISO 18935 ratings.

Printer/Paper	Image	Reason
Dye sublimation	Moderately resistant	Minor gloss and color change
Ink jet dye on plain paper	Not resistant	Severe color change and paper cockling
Ink jet pigment on plain paper	Not resistant	Severe paper cockling
Ink jet dye on porous photopaper	Moderately resistant	Minor gloss and color bleed
Ink jet dye on polymer photopaper	Not resistant	Dissolution of image layer
Chromogenic	Not resistant	Severe gloss change

Table XII. Comparison of digital print materials exposed to flood.

	Sample A	Sample B	Sample C	Sample D	Sample E	Sample F
ΔE black	1	7	1	2	Destroyed	1
ΔE cyan	1	37	1	5	Destroyed	1
ΔE magenta	1	67	2	8	Destroyed	3
ΔE yellow	1	58	1	4	Destroyed	2
Gloss change	40	1	2	15	71	62
Text readable	Yes	Yes	Yes	Yes	No	Yes
Image coating loss	0	0	0	0	3	0
Planar distortion	1	2	2	1	2	1

- Both text documents and pictorial images should be tested.
- The three-tiered evaluation system in ISO 18935 is inadequate for cultural heritage purposes.
- Modes of failure are independent and should be measured and evaluated separately.
- Some failure types are totally destructive and others maybe repairable, so they should not be equated when determining material sensitivity to flood.

RECOMMENDATIONS FOR FUTURE WORK

Predictive flood testing is difficult because actual flood experiences can vary greatly. During floods, prints can be exposed to clean or dirty water for various lengths of time. Clean water can vary in its chemical makeup, but dirty water can vary even more in its chemical as well as particulate and biological contents. All flood waters will vary in temperature and flow rates. Further examination of all these issues may improve the understanding of how digital prints degrade in these unfortunate events.

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