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A novel replicability survey tool to measure and promote reproducibility in hydrology

Authors: James Stagge (The Ohio State University), David Rosenberg (Utah State University), Adel Abdallah (Utah State University), Hadia Akbar (Utah State University), Nour Attallah (Utah State University), and Ryan James (Utah State University)

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Datasets:

Repository Name	Dataset Title	Dataset Accession Number	URL	Reviewer Passcode
	jstagge/reproduc_hyd: Source code accompanying		https://github.com/jstagge/reproduc_hyd	

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A novel replicability survey tool to measure and promote reproducibility in hydrology

James H. Stagge[1,2*], David E. Rosenberg[1], Adel M. Abdallah[1], Hadia Akbar[1], Nour A. Attallah[1], Ryan James[1]

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1. Utah State University, Department of Civil and Environmental Engineering, Logan, UT 84321

2. The Ohio State University, Department of Civil, Environmental and Geodetic Engineering, Columbus, OH 43210

*corresponding author(s): James H. Stagge (stagge.11@osu.edu)

Abstract

There is broad interest to improve the reproducibility of published research. We developed a simple survey tool to assess the 1) availability of data, models, code, directions, and other digital artifacts, and 2) replicability of results published in peer-reviewed journal articles. We used the tool to assess 360 random sampled articles of the 1,989 articles published in 2017 in six well-regarded hydrology and water resources journals. Like several prior studies, we replicated results for just a small fraction of articles (1.6%; estimated between 0.6% and 6.8% for all 1,989 articles with 95% confidence). Unlike prior studies, the tool helped identify key bottlenecks to make work more reproducible. These bottlenecks include: only some digital artifacts available (44% of articles), no directions (89%), or all artifacts available but results not replicable (5%). These results suggest the tool (or extensions) can help authors, journals, funders, and institutions to self-assess the availability and replicability of manuscripts, provide feedback to authors to improve manuscript reproducibility, and recognize and reward reproducible articles as examples for others to follow.

Introduction

The science community is broadly interested to improve the reproducibility of research [1, 2, 3, 4, 5]. While exact definitions of reproducibility vary [6, 7, 1, 8, 9, 10, 11, 12, 13], one overarching theme is that reproducibility requires multiple, progressive components such as (i) all data, models, code, directions, and other digital artifacts used in the research are available for others to reuse (hereafter, “availability”; [14, 15, 16], (ii) the artifacts can be used to exactly replicate published results (replicability, sometimes called bit or computational reproducibility; [17, 18], and (iii) existing and new datasets can be processed using the artifacts to reproduce published conclusions (reproducibility).

Replicable and reproducible scientific work is currently uncommon because of misaligned incentives and poor coordination among authors, journals, institutions, and funding agencies that conduct, publish, and support scientific research [19, 20, 8]. For example, making artifacts available requires authors to document additional materials [21, 22] and learn new skills and technologies [23]. Authors may worry that shared materials will never be used [24, 9] or that other scientists will scoop them on follow-up studies [25]. Further, universities typically reward peer-reviewed journal publications, rather than data repositories or documentation, while current scientific culture rewards novelty rather than replicating prior efforts [17, 2].

Several efforts are underway to encourage more reproducible science [8]. Authors can share research materials in a growing number of online repositories such as Github, Figshare, Harvard Dataverse, Dryad, and HydroShare. Institutional libraries are transitioning to offer online repositories to house digital research artifacts [26, 27, 28, 29]. Within our field of hydrology and water resources, recent tools provide environments to repository data and allow software to operate on the data as well as create virtual environments that package code, data, and a working operating system to reduce problems of incompatibility (e.g., [30, 31]). Authors can assign digital object identifiers (DOIs) to research packages to create persistent links and use umbrella research licenses to describe the manner in which these digital artifacts and their associated paper may be legally used by others [19]. Additionally, authors can specify the level of reproducibility that readers and reviewers can expect from each publication. And yet, despite these powerful tools, few authors are making their work available for others to replicate or reproduce.

To quantify the current state of reproducible science in hydrology and to understand the factors preventing more replicable or reproducible publications, we present here a simple 15-question survey tool (Fig. 1) designed to assess the availability of digital artifacts and replicability of results in peer-reviewed journal articles (see Methods). We use this survey tool to assess 360 stratified random-sampled articles from the 1,989 articles published in 2017 across six reputable hydrology and water resources journals. Sampling was stratified by journal and reproducibility keywords of interest. Results identify bottlenecks to making digital artifacts available and replicating output. We also use results to generalize replicability for the entire sample of articles, test a hypothesis about use of keywords to identify replicable articles, compare the effectiveness of different journal data availability policies, and highlight how authors, journals, funders, and institutions can use the enclosed survey tool to encourage, recognize, and reward the publication of more reproducible articles.

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Results

Applying our survey tool to 360 random-sampled hydrology articles published in 2017 shows a decreasing number of articles are able to satisfy the progressively stricter reproducibility requirements of artifact availability and ultimately replication of published results (Fig. 2). For example, 70.3% of the 360 sampled articles stated some materials were available, but we could only access 48.6% of those materials online (Fig. 3). Only 5.6% of sampled articles made data, model/code, and directions publicly available while just 1.1% of sampled articles made artifacts available and were fully replicated. We partially replicated an additional 0.6% of articles.

Artifact Availability

Across all journals, the most common artifact provided was input data, followed by code/model/software, and then directions to run (Fig. 4). Other artifacts, such as hardware/software requirements, common file formats, unique and persistent digital identifiers, and metadata, were made available at much lower rates than the primary artifacts. Articles published in Environmental Modeling & Software (EM&S) made artifacts available online at a high rate and these articles also provided data/model/code, directions, hardware/software requirements, common file formats, and metadata at rates 2 to 3 times the next most frequent journal.

Sampled articles use different methods to make artifacts available and these methods differ markedly across journals (Fig. 4). EM&S had the largest proportion of sampled articles that made at least some artifacts available online (61.9%). By contrast, Hydrology and Earth Systems Sciences (HESS) and Water Resources Research (WRR) had high percentages of articles where materials were only available by first author request (38.5-40.2%). Otherwise, the Journal of Hydrology (JoH), Journal of the American Water Resources Association (JAWRA), and Journal of Water Resources Planning and Management (JWRPM) had large proportions of articles where data was not available or was available within the article and supplemental material.

Replication of Results

Twenty sampled articles (5.6% of total sampled articles) made the required input data, software/model/code, and directions available, allowing an attempt at replicating published results. We were able to fully replicate results for four articles [32, 33, 34, 35] and partially replicated results for two additional articles [36, 37]. We were unable to replicate results for four articles [38, 39, 40, 41], which nonetheless appeared to provide the necessary materials. During the process to replicate results, we found 10 of the 20 articles did not have all the required artifacts, despite being initially considered for replication testing. Reasons we only partially replicated results for two articles and did not replicate results for four articles included unclear directions (4 articles), did not generate results (3 articles), hardware/software error (2 articles), or results differed from the publication (1 article; some articles had multiple reasons). The survey permitted multiple selections for this question. A common issue across cases where we did not generate results was that folder and file locations were hard-coded to work on the author's computer. If these issues were obvious, we tried, with limited success, to fix them. Other cases pointed to general data gateways, like the USGS streamgauge network, with no further details or required expensive or proprietary software. Of the 10 articles that had all artifacts available, five were published in EM&S, two articles were published in HESS, and the remaining journals each had one article.

Estimated Replicability for Population

Because the stratified sampling method oversampled articles with certain reproducibility keywords, we used bootstrap resampling (see Methods) to estimate that 0.6% to 6.8% of all 1,989 articles published in 2017 in the six journals tested here would be replicable (95% confidence interval). We estimated 28.0% (23.1-32.6% confidence interval) of all articles published in these journals during 2017 provided at least some of the artifacts necessary for replicability (Fig. 5, black). EM&S differed from other journals by having a large proportion of articles with some or all data available (31.8-64.0%) and relatively high estimates of replicability (Fig. 5).

Using Keywords to Identify Replicable Articles

We found that five of the six articles with some or complete replicability had certain reproducibility-related keywords of interest in their abstracts (full list in Methods). This positive hit rate (4.2%) for articles with reproducibility keywords is significantly greater than articles without (0.4%; 2-sample Chi-Squared test with Yate's continuity correction ($p = 0.014$)). These findings confirm the value of reproducibility keywords to identify replicable articles and reaffirm the difficulty to know at the outset whether the results presented in an article are replicable.

Time Required to Determine Availability and Replicability

We surveyed and analyzed the time required to complete the survey to show the incremental effort required to determine the availability of article artifacts and replicability of results (Fig. 6). For example, it took us as little as 5 to 14 minutes (25-75% range) to determine the availability of input data, model/software/code, and directions and upwards of 25 to 86 minutes (25-75% range) to fully replicate results with outliers of 25 and 200 minutes (minimum and maximum). There were no statistically detectable differences in the time between journals to determine availability of digital artifacts or replicate results.

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Reproducibility and Journal Policies

Among the six hydrology and water resources journals we studied, the HESS and WRR policies effective during the 2017 review period require articles to state how data, models, and code can be accessed. In contrast, the 2017 policies by EM&S, WRPM, JoH, and JAWRA simply encouraged this practice. EM&S further recommends articles include an explicit "Software and/or data availability" section within the article and requires authors to make software essential to the paper available to reviewers during the review process (Supplemental Material Table S1).

These journal data availability policies partially but not fully explain differences in artifact availability and result replicability by journal. For example, EM&S, which only encourages authors to make artifacts available, had the highest rate of articles that made artifacts available (Fig. 3) and this high rate persisted across nearly every artifact category (Fig. 4). Although EM&S used "should" instead of "must" statements, their policy was by far the most specific for papers with a software component (Supplemental S1). This may explain their high participation rate. EM&S is also a software-focused journal, which may attract papers and authors that are more conscious of reproducible software. In contrast, HESS and WRR, which require data availability statements, had lower percentages of articles that made artifacts available and more papers that direct readers to the authors or third parties for data, models, or code (Fig. 3). These directional statements tend to appear in the Data Availability section of HESS articles and the Acknowledgements of WRR articles. The final group, JoH, JAWRA, and JWRP&M, that also encouraged authors to make artifacts available, had high proportions of articles without available digital artifacts (Fig. 3). The HESS and WRR policies that require data availability statements appear to encourage authors to select options like contact the author rather than work to provide a research article and supporting materials that are available, replicable, and reproducible. In July 2018, JWRP&M switched to start requiring authors to state the availability of data, models, and code, similar to HESS and WRR [42].

Discussion

Our findings of low replicability of research published in six hydrology and water resources journals in 2017 mirrors low rates of replicability previously reported in psychology (100 experiments; [2]), computer systems research (613 articles; [43]), and across articles published in Science (204 articles; [5]). Unlike those studies, our survey tool additionally identified bottlenecks to making all digital artifacts available and replicating results. Here, we discuss how results for our study in hydrology and water resources can inform broader use of the survey tool by authors, journals, funders, and institutions to improve the reproducibility of published scientific research.

Authors. Authors can use the survey tool as a checklist to self-assess the availability of data, models, code, and directions and replicability of their work before submitting work for publication. The tool can help identify missing components that, if provided, will improve reproducibility. For example, our results showed that, for all journals, the number of sampled articles with code/data/software was consistently 2 to 3 times higher than the number of articles that additionally provided directions (Fig. 4). If authors used the tool and subsequently provided directions to use their materials, the tool could potentially double the number of articles which could reasonably be tested for replicability. Another bottleneck was a large fraction of authors who chose not to make artifacts available or only made artifacts available by author or third party request. Authors can look to the 10 articles we found that made all digital artifacts available to see easy-to-access platforms to provide access. These platforms included GitHub (6 articles), HydroShare (1 article), journal supplementary material (1 article), a custom website (1 article), or Figshare (1 article). Authors who bundled their code and data together in a single GitHub repository further allowed us to download the entire project, with a higher likelihood that code pointed to valid file directories.

Journals. Journals can use the survey tool to assess the availability of data/model/code and directions, replicability of results of new submissions, and provide feedback to authors. Alternatively, journals can require that authors use the survey tool to self-check their work prior to submission. Feedback can be crucial as our study showed that a very low fraction of articles provided all the required artifacts. However, when artifacts were available, we fully or partially replicated results for 6 out of 10 articles. We also found that time to assess the availability of artifacts was typically less than 15 minutes, while time to replicate results was much longer. The combination of these findings suggests that promoting inclusion of digital artifacts through a relatively quick availability survey could pay significant dividends for replicability. We leave open whether responsibility for assessment should fall on a journal editor's assistant, associate editor for reproducibility, reviewers, or others. With a tool to measure reproducibility of published articles, journals could also track reproducibility over time. Tracking and publishing this information would benefit the journal as a promotional tool to show journal commitment to reproducible science. Tracking would also allow journals to acknowledge articles and authors that reach certain reproducibility standards. For example, show a bronze, silver, or gold medal icon on article webpages to recognize and reward progressively greater reproducibility corresponding to availability, replicability, and reproducibility. These badges would simultaneously communicate the expected level of reproducibility of published work. In our study, we are excited to award silver badges to the four articles whose results we fully replicated [32, 33, 34, 35] and bronze badges to six articles that made all artifacts available [36, 38, 39, 40, 41, 37]. This recognition also makes it easier for authors to find and emulate excellent reproducibility practices. Cross-journal indices could further aggregate reproducibility metrics and encourage journals and authors to improve the reproducibility of their research portfolios. To oversee these journal efforts, we envision a new role for an Associate Editor of Reproducibility to develop journal data availability and reproducibility policy, manage reproducibility evaluations, and advocate for best reproducibility practices.

Funders and Institutions. Similar to journals, funders and institutions can use the survey tool to assess artifact availability, verify replicability of results, and recognize or reward authors whose work achieves bronze, silver, and gold levels of reproducibility. Alternatively, funders and institutions could use reproducibility assessments made by journals. Funders can encourage authors to use the survey tool to self-check work prior to submitting progress or final reports or use the tool to check the reproducibility of work authors submit. Use of the tool could help verify that author submissions fulfill requirements of funder data management policies and help direct authors to improve the reproducibility of their work. Institutions could also use the survey tool to determine and post the expected level of reproducibility of author work deposited into institutional repositories.

Together, these actions by authors, journals, funders, and institutions can help nudge authors further along the reproducibility continuum to make their digital artifacts more available and to replicate published results. While these proposed policy nudges represent small shifts targeted at particular actors in the science community, this approach can produce large effects collectively [44], particularly when all parties agree that the shift will provide a net benefit, as for reproducible science. Each individual nudge is made possible by using a survey (or similar) tool to measure and quantify the availability of digital artifacts, replicability of published results, and reproducibility of findings. We welcome discussion to improve the survey tool aimed at improving the reproducibility of our science.

Methods

Online Survey Tool

The authors translated definitions of availability, replicability, and reproducibility into a 15-question Qualtrics Research Core (Qualtrics) online survey (Fig. 1). The Qualtrics survey format has been converted into a publicly available version, provided here as an example (`https://goo.gl/forms/95S4y9BdPmVqMtm02`). The survey progressed from soliciting metadata about the article (Questions 1-4), to testing availability of artifacts (Q5-9), and ultimately testing replicability of results (Q10-14). Green or yellow shaded answers (Fig. 1) were required to progress to the next question so that survey questions followed the availability and replicability progression. Selecting a red-shaded answer stopped progression and directed the reviewer to a final question that asked how many minutes the reviewer spent to reach their stopping point (Q15). This time to complete was self-reported by reviewers rather than using the built-in Qualtrics timer so reviewers could consider the entire time spent reading and assessing the published article, rather than the time completing the survey.

The authors developed the tool over four months in Fall 2017 and pre-tested it in early 2018 on a sub-sample of five articles that spanned the availability and replicability progression. From our experience pre-testing and to improve use of the tool, we reworded some questions, altered the survey logic, discussed and addressed inter-reviewer variability. Later, after we had reviewed 23% of sampled articles, we added a final question (Q15) to ask how much time it took to complete the survey.

Selection of Articles

360 peer-reviewed articles were random stratified sampled from the 1,989 articles found in Scopus that were published in 2017 in six well-regarded hydrology and water resources journals (measured by impact factor and reputation). The six journals were Hydrology of Earth Systems Sciences (HESS), Environmental Modeling & Software (EM&S), Journal of the American Water Resources Association (JAWRA), Journal of Hydrology (JoH), Journal of Water Resources Planning and Management (JWRPM), and Water Resources Research (WRR). Stratified random sampling was approximately proportional to the number of articles published in each journal in 2017, with extra weight placed on articles with a set of reproducibility-related keywords (Table M1).

We further adjusted the stratification so each journal had at least 30 articles (JAWRA and JWRPM were oversampled). Similarly, we oversampled articles with the keywords: analytical software, application programs, C++, cloud computing, computational reproducibility, computer modeling, computer programming, computer software, computer software usability, computer-based models, development and testing, engineering software, fortran, freely available data, freely available software, github, hardware and software, java, open code, open source, replicative validation, scientific software, code, python, cran, and http. Of the 120 articles published in the six journals in 2017 that had at least one keyword, we sampled 119 articles, principally to retain at least 15 non-keyword articles for each journal with an approximately 2:1 non-keyword to keyword ratio overall.

Table M1: Number of articles published in 2017 and number of articles sampled by journal.

	EM&S		HESS		WRR		JoH		JAWRA		JWRP&M	
	2017	Sample	2017	Sample	2017	Sample	2017	Sample	2017	Sample	2017	Sample
Keyword	49	48	9	9	23	23	24	24	7	7	8	8
Non-key word	181	15	319	43	511	59	645	79	102	23	111	22
Total	230	63	328	52	534	82	669	103	109	30	119	30

Each author was randomly assigned 60 articles stratified by journal to assess the availability of article artifacts (Q1-9). After identifying all publications that had the available artifacts, we re-assigned reviewers to assess whether the published results could be replicated (Q1-15). Reassignments matched article software to the reviewer most familiar with those tools. The Qualtrics online format allowed us to both simultaneously and asynchronously assess journal articles and store survey responses in an accompanying Qualtrics database. After all availability and replicability assessments were complete, we exported results from the Qualtrics database to a text file which was processed in R to generate figures, tables, and results. Time spent to complete the survey (Q15) was analyzed for three key stopping points: no artifacts available (Q5), availability of artifacts (Q9), and replicability of results (Q13).

Population Estimates

Bootstrap resampling was used to estimate the overall percentage of articles from all n=1,989 articles published in 2017 in the six journals while adjusting for keyword and journal sampling. Sampled articles were sorted into six mutually exclusive categories that were stopping points in the survey: Data-less or review, Author or Third Party Only, No availability, Some Availability, Available but not reproducible, and Some or All Replicable. "Some availability" included articles with one or two data/model/code, and direction elements of the three required elements (Q7). "Available but not replicable" articles had all three required elements available on the initial review, but either could not be replicated or were found to be missing key elements when replication was attempted.

The resampling approach was based on 5,000 simulations of the population. For each simulation, the 360 sampled articles were inserted directly based on the survey results, assuming that these were known exactly. Estimates for the remaining 1,629 unsampled articles were simulated based on survey results for the sampled articles in their stratified category, i.e. journal and keyword/non-keyword. Uncertainty for the unsampled articles was calculated using the approach of Sison and Glaz [45], assuming the six potential levels of availability/replicability represent multinomial proportions of categorical data [46].

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Author Contributions

Stagge, Rosenberg, James, and Abdallah conceived the idea for a survey tool to measure the reproducibility of journal articles. Stagge and Rosenberg led the design and refinement of the tool and Abdallah implemented the design. All authors participated equally in the use of the survey tool to evaluate the reproducibility of articles. Stagge led the results analysis, visualization, and writing of the first draft. Stagge and Abdallah made all article digital artifacts available online. Rosenberg rewrote the initial draft. All authors reviewed and approved the final draft prior to submission.

Availability and Replicability of Research Artifacts

The survey tool, Qualtrics results, and all code used for analysis presented in this article are available online through GitHub (`https://github.com/jstagge/reproduc_hyd`) or through a permanent repository [47]. Please cite this repository for any use of the related data or code. Additionally, results can be replicated using RStudio deployed in the cloud using MyBinder through the GitHub website. An open Google Forms version of the survey tool is available for readers to use, modify, and extend. (`https://goo.gl/forms/95S4y9BdPmVqMtm02`).

Competing financial interests

The author(s) declare no competing financial interests.

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Figures Legends

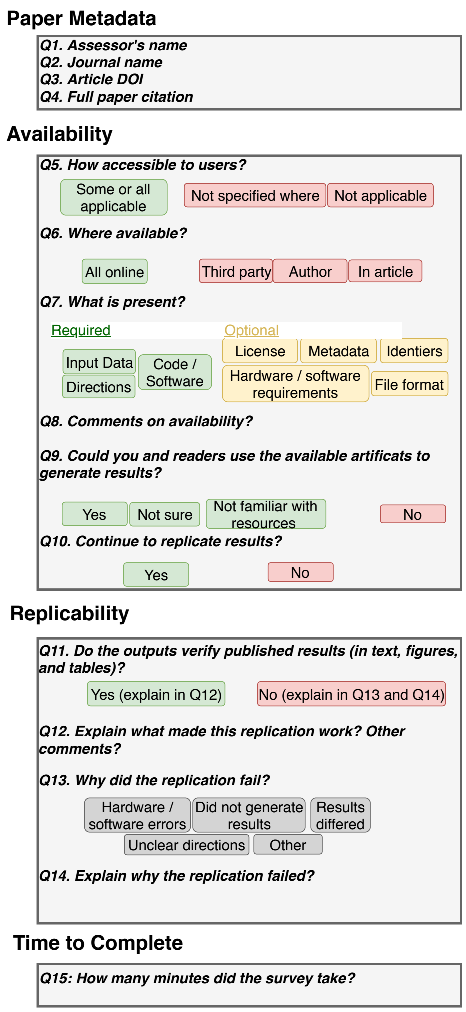

Figure 1: Survey questions to assess journal article data availability and replicability. Green and grey answers continue to the next question, while red answers skip to question 15.

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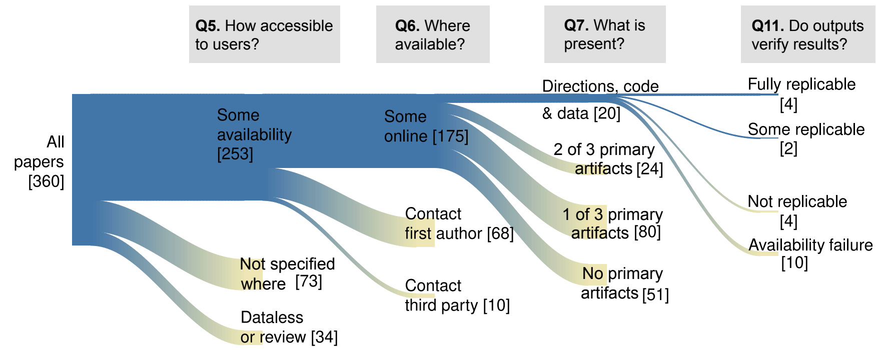

Figure 2: Number of papers progressing through the survey questions to determine availability and replicability requirements.

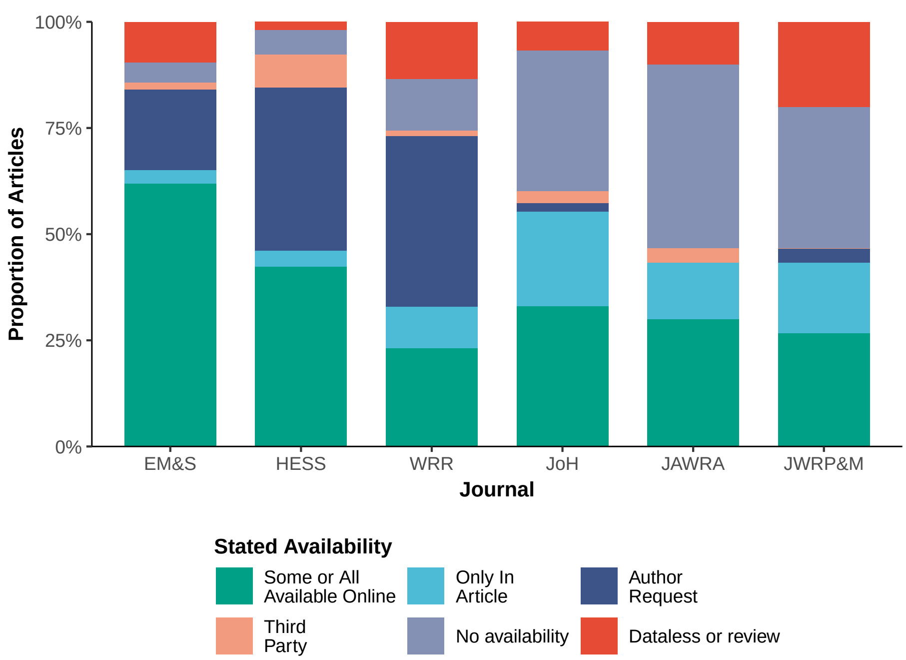

Figure 3: Data, model, code availability by journal (summary of Q4 and Q5).

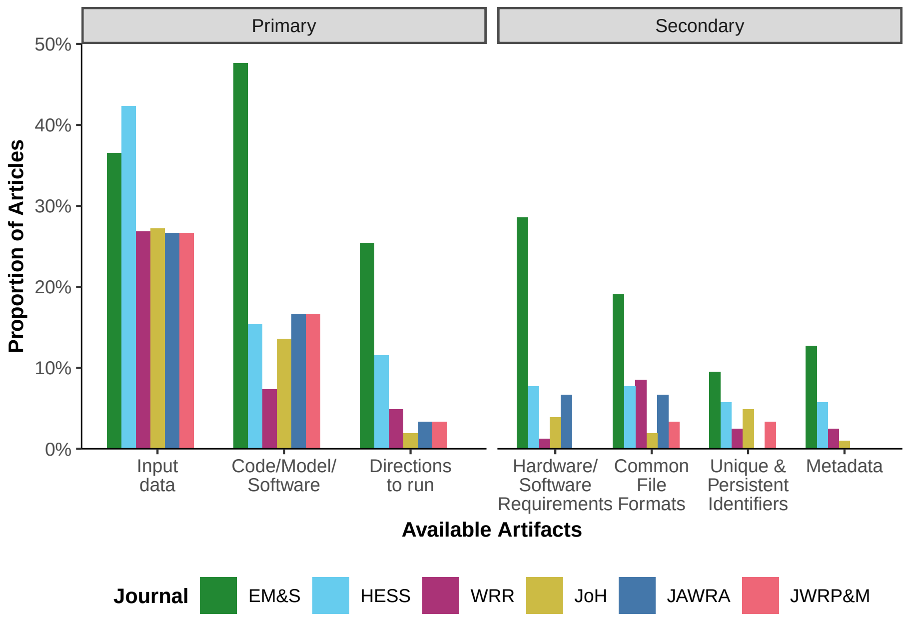

Figure 4: Availability artifacts organized by journal. All percentages are based on the total number of sampled papers for each journal.

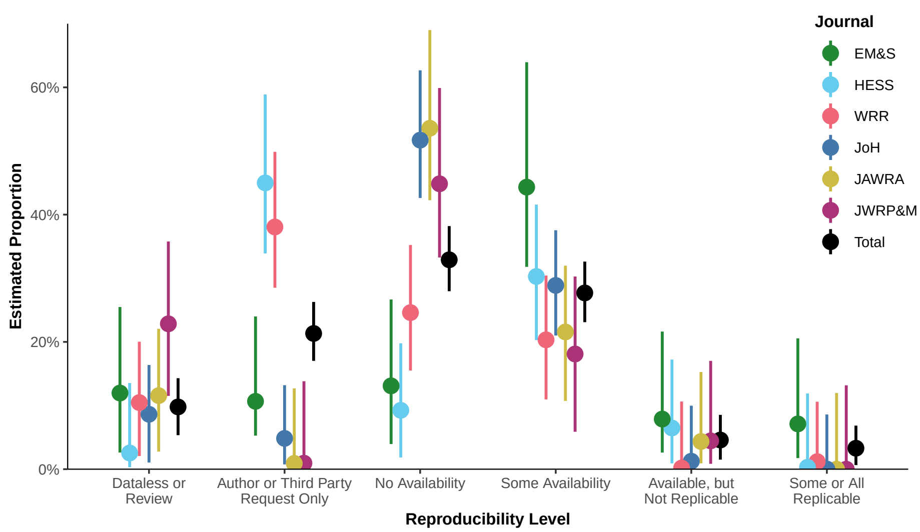

Figure 5: Population estimate of reproducibility for all papers published in 2017. Results are sorted by journal, with "Total" representing all 6 journals. Median estimate is represented by a point, vertical bars show the 95% confidence interval.

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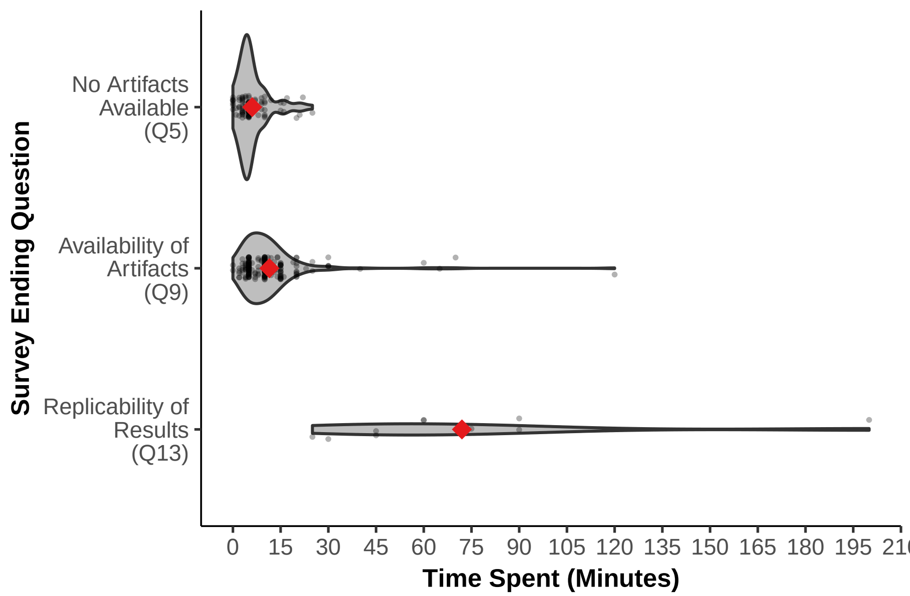

Figure 6: Self-reported time to complete survey organized by the survey's ending question. Each reviewed paper is shown by a black dot, while the mean is represented by a red dot. Distribution density is shown by width.

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Supplementary Material

Table S1: Summary of journal data policy snapshots in the selected water resources journals as of December 2017. The key word indicating the level of the requirement is highlighted in bold.

Journal	**Data Policy Statement**	**URL**
Environmental Modeling & Software (EM&S)	Where appropriate, a software/data availability section **should** be provided, containing as much of the following information as possible . . . When a software component is an essential part of the paper presentation, authors **should** be prepared to make it available to reviewers during the review process. To preserve the anonymity of reviewers, the authors **should** make the software available for a download.	https://www.elsevier.com/journals/environmental-modelling-and-software/1364-8152/guide-for-authors
Hydrology and Earth Systems Science (HESS)	Each manuscript **must** have a final Data Availability section that states how the underlying research data can be accessed.	http://www.hydrology-and-earth-system-sciences.net/about/data_policy.html
Water Resources Research (WRR)	AGU's Data Policy states that all data necessary to understand, evaluate, replicate, and build upon the reported research **must** be made available and accessible whenever possible.	http://publications.agu.org/author-resource-center/publication-policies/data-policy/
Journal of the American Water Resources Association (JAWRA)	JAWRA **encourages** authors to share the data and other artefacts supporting the results in the paper by archiving it in an appropriate public archive.	https://onlinelibrary.wiley.com/page/journal/17521688/homepage/forauthors.html
Journal of Hydrology (JoH)	To foster transparency, we **encourage** you to state the availability of your data in your submission.	https://\www.elsevier.com/journals/environmental-modelling-and-software/1364-8152/guide-for-authors
Journal of Water Resources Planning and Management (JWRPM)	Authors are **encouraged** to use Supplemental Data to show all necessary data	https://ascelibrary.org/doi/pdf/10.1061/9780784479018.ch03

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Paper Metadata

Q1. Assessor's name
Q2. Journal name
Q3. Article DOI
Q4. Full paper citation

Availability

Q5. How accessible to users?

Some or all applicable | Not specified where | Not applicable

Q6. Where available?

All online | Third party | Author | In article

Q7. What is present?

Required

Input Data | Code / Software | Directions

Optional

License | Metadata | Identiers | Hardware / software requirements | File format

Q8. Comments on availability?

Q9. Could you and readers use the available artificats to generate results?

Yes | Not sure | Not familiar with resources | No

Q10. Continue to replicate results?

Yes | No

Replicability

Q11. Do the outputs verify published results (in text, figures, and tables)?

Yes (explain in Q12) | No (explain in Q13 and Q14)

Q12. Explain what made this replication work? Other comments?

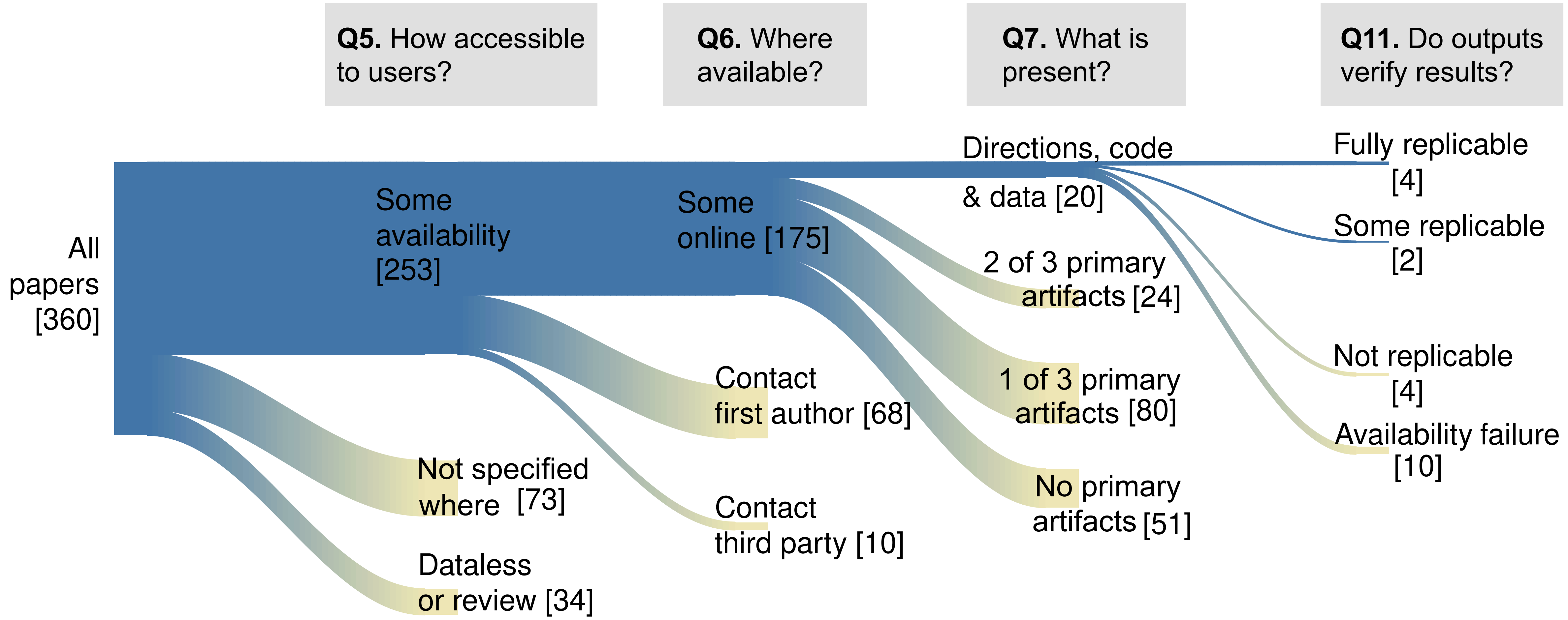
Q13. Why did the replication fail?

Hardware / software errors | Did not generate results | Results differed | Unclear directions | Other

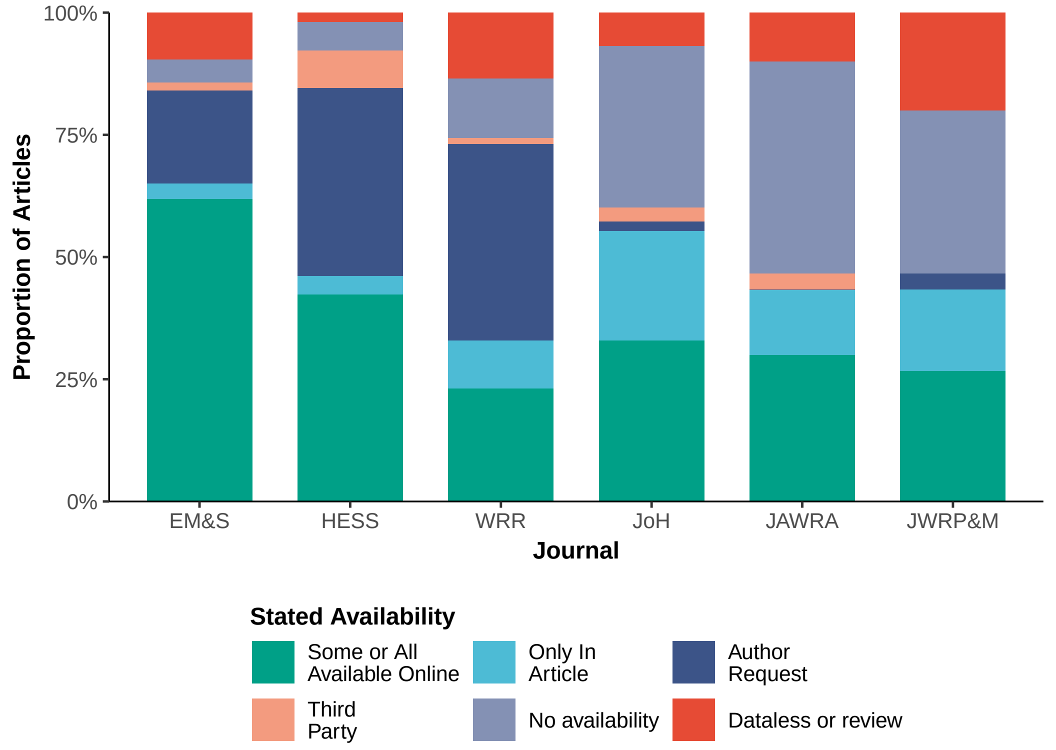
Q14. Explain why the replication failed?

Time to Complete

Q15: How many minutes did the survey take?



Q5. How accessible to users?
Q6. Where available?
Q7. What is present?
Q11. Do outputs verify results?
All papers [360]
Some availability [253]
Not specified where [73]
Dataless or review [34]
Some online [175]
Contact first author [68]
Contact third party [10]
Directions, code & data [20]
2 of 3 primary artifacts [24]
1 of 3 primary artifacts [80]
No primary artifacts [51]
Fully replicable [4]
Some replicable [2]
Not replicable [4]
Availability failure [10]


100%
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Proportion of Articles
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Only In Article
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No availability
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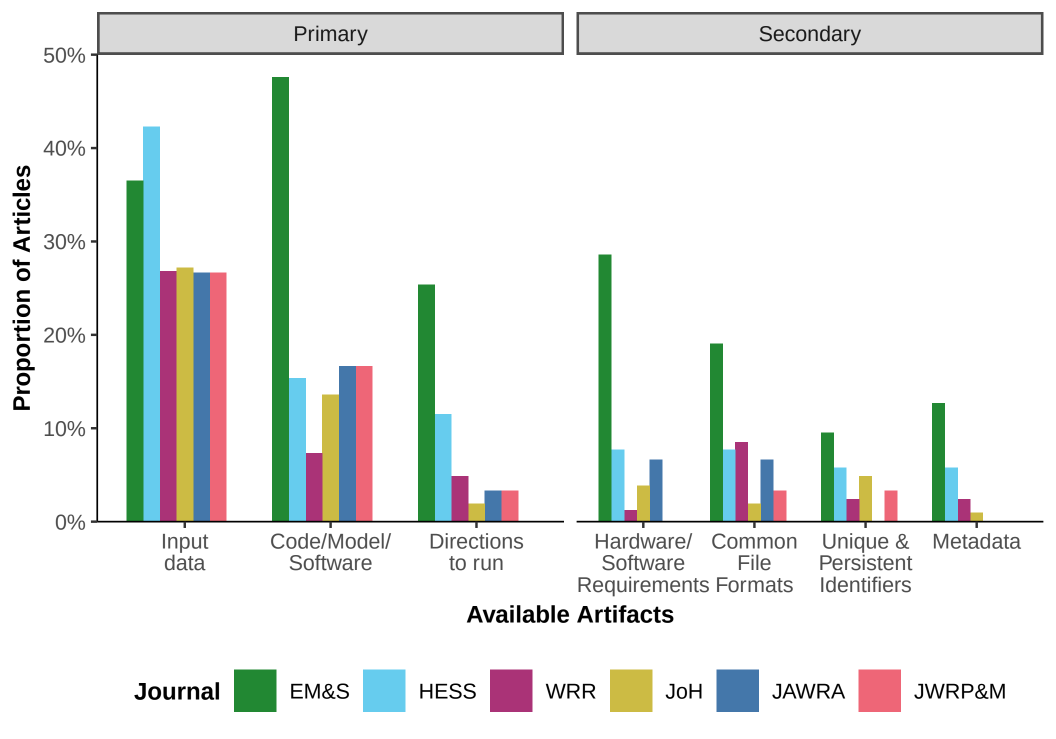

Primary
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Proportion of Articles
50%
40%
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Input data
Code/Model/ Software
Directions to run
Hardware/ Software Requirements
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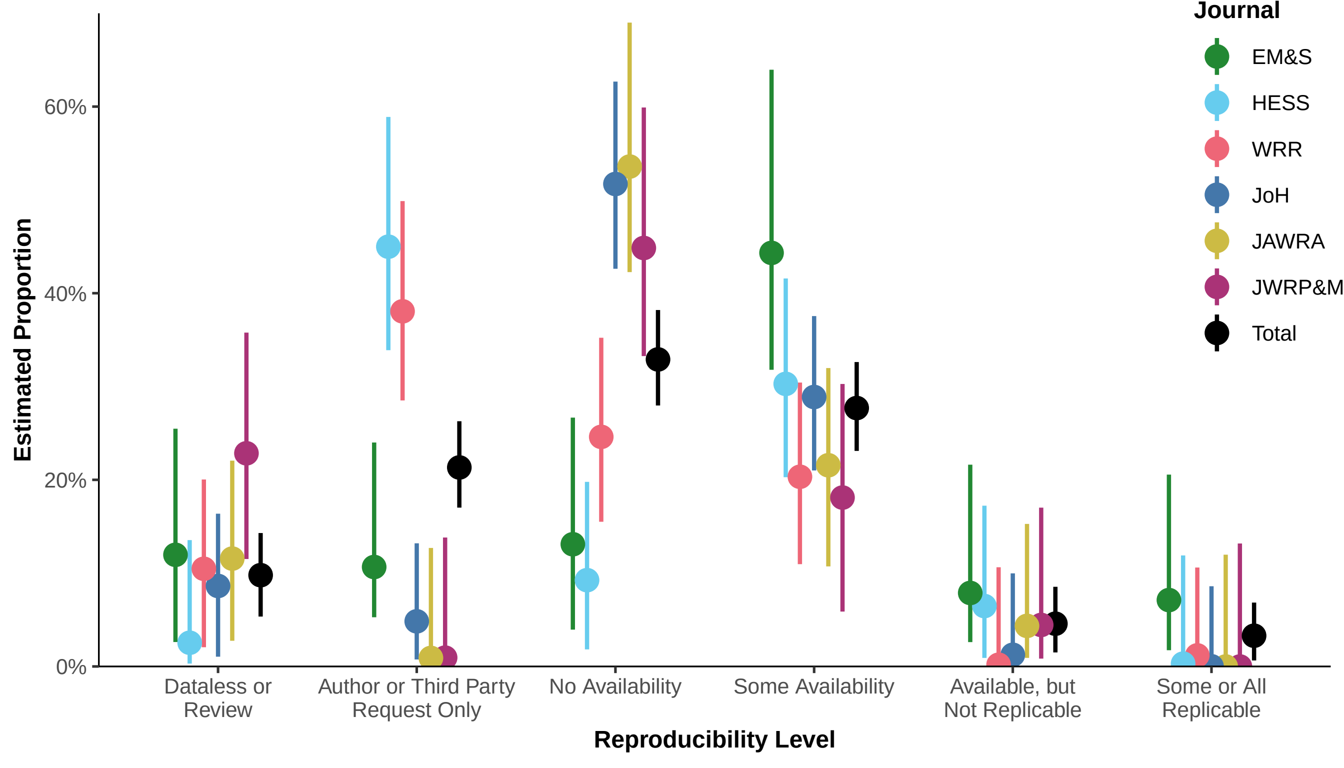
Journal
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Author or Third Party Request Only
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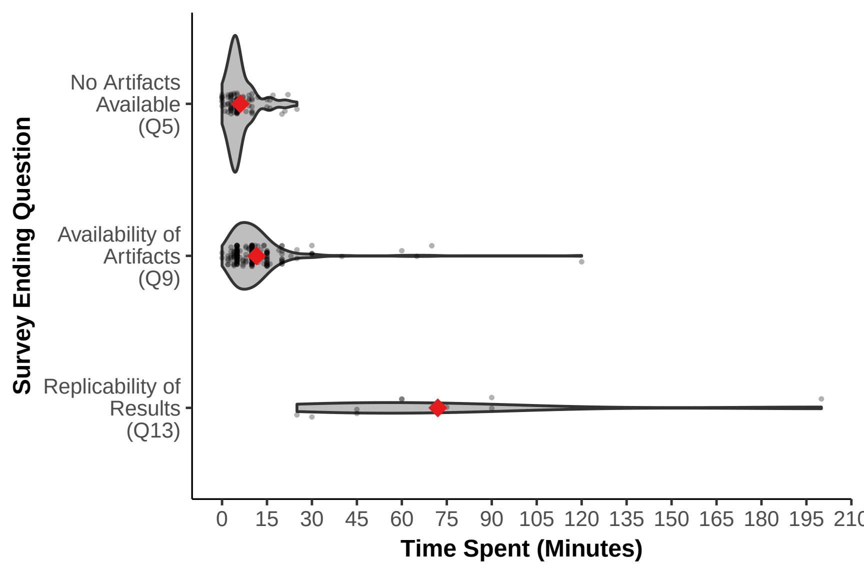
Some or All Replicable
Reproducibility Level


No Artifacts Available (Q5)
Availability of Artifacts (Q9)
Replicability of Results (Q13)
Survey Ending Question
0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
Time Spent (Minutes)

	EM&S		HESS		WRR		JoH		JAWRA		JWRP&M	
	2017	Sample	2017	Sample	2017	Sample	2017	Sample	2017	Sample	2017	Sample
Keyword	49	48	9	9	23	23	24	24	7	7	8	8
Non-key word	181	15	319	43	511	59	645	79	102	23	111	22
Total	230	63	328	52	534	82	669	103	109	30	119	30