Field Scale Demonstration of Fly Ash Amended Bioretention Cells for Stormwater Phosphorus Removal: A Review of 12 Years of Work

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Abstract: In 2007, ten bioretention cells were constructed in Oklahoma as part of a full-scale technology project to demonstrate stormwater phosphorus reduction. The filter media used was amended with 5% Class C fly ash by weight to increase phosphorus and heavy metal retention. In 2014, core samples were collected from four of the cells, and three were instrumented for continuous water monitoring for the following year. This paper will review the design, construction, computer modeling of phosphorus retention, and measured phosphorus removal after seven years of operation. Total phosphorus retained in the sampled cells showed reductions in effluent water concentrations of 68 to 75%, while total effluent mass reductions of 51 to 93% were achieved. Total phosphorus accumulation in the cells measured in cores ranged from 0.33 to 0.60 kg/year, which was somewhat greater than the annual calculated effluent reduction of 0.27 to 0.41 kg/year. While good, phosphorus retention was not as high as computer modeling predicted. Other research on the cells, including hydraulics, heavy metal adsorption, and microbial transport, is summarized. Experimental challenges with phosphorus extraction from samples are also discussed. All experience and results suggest that fly ash amendments are an effective option for phosphorus removal in bioretention cells.

Keywords: filter media; water quality; extraction methods; core sampling; water sampling; Oklahoma

1. Introduction

Ten bioretention cells (BRC) were constructed in 2007 as part of a US EPA 319h demonstration project administered by the Oklahoma Conservation Commission with the goal to reduce phosphorus levels in Grand Lake, Oklahoma (OK) [1]. Like other water in the US, Grand Lake experiences algae blooms and other water quality impairments due largely to excess nutrients [2]. Eight of the constructed cells are located in Grove, OK, as shown in Figure 1. Two additional BRC were constructed in Stillwater, OK in 2008. The watershed drainage area ranged from 0.07 to 0.77 ha and is consistent with potential applications in urban areas [3]. Land use on the cells’ drainage varied. Two are residential, six are public or educational, and two are commercial. These cells were unique in three aspects. First, they incorporated Class C fly ash into the filter media to greatly increase phosphorus and metal retention. Secondly, they utilized surface sand plugs to increase infiltration and ensure that the cells would not pool water for more than two days. Finally, and perhaps most importantly, there has been extensive laboratory testing and computer modeling carried out both before and after their construction to better understand the BRC’s long-term removal of multiple pollutants, including phosphorus, heavy metals, and microbes.
BRC’s long-term removal of multiple pollutants, including phosphorus, heavy metals, and microbes. Researchers should consult the citations for relevant related literature, experimental procedures, data and other factors. Marvin et al. [5] have recently presented a systematic literature review of phosphorous sorption in bioretention media. They note that a number of other researchers have more recently conducted laboratory or mesocosm scale tests of phosphorus retention with fly ash amended filter media [6–12]. Those tests showed that fly ash is generally superior to other additives for phosphorus reduction. However, Marvin et al. [5] also note that only four field scale bioretention studies have been published on any phosphorus adsorbing amendment [13–16]. Finally they note that the Oklahoma BRC are the only cells to have undergone testing after several years of service.

2. Fly Ash

Fly ash is a combustion product of coal fired power plants that exits with the flue gases and is collected by electrostatic precipitators, gas centrifuges, or filter bags. United States production in 2019 was 29 million tons, of which 18 million tons were used in construction and consumer products [17]. Fly ash should not be confused with other coal combustion products, such as bottom ash, boiler slag, and flue gas desulfurization gypsum.

Since fly ash is a byproduct generated in large quantities, most coal plants give it away to responsible companies to haul it off. Thus, the wholesale price is the cost of transportation, a few dollars a ton. The authors’ experience is that power companies are supportive of an environmental application of their waste, and the fly ash used here was obtained free. In addition, since fly ash is a commonly used concrete additive, many cement suppliers sell it in bulk. The primary safety concern with the use of fly ash is the fine
dust particles with large amounts of silica. Workers should use respirators and the public should not be exposed to the dust during storage and handling. Fly ash is not classified as a hazardous waste [18].

Zhang et al. [19,20] carried out pollutant retention screening tests on several materials including fly ash, limestone, and expanded shale. Unweathered Class C fly ash [21] was obtained from the Grand River Energy Center, near Chouteau, OK, and the Sooner Power Plant at Red Rock, OK. The fuel source for both plants was sub-bituminous coal from the Powder River Basin, Wyoming. Table 1 lists properties for the Sooner fly ash. The Grand River fly ash was nearly identical. Chemical composition, was determined by X-ray fluorescence (Activation Laboratories Ltd., Ancaster, ON, Canada). Metal leaching potential was determined by the TCLP Method 1311 [22]. All tested metals concentrations were well below the regulatory level [23].

Table 1. Fly ash mineral composition, metal leaching, and bulk properties [20].

| Mineral | Content (%) | Metal | Concentration in Leachate (mg/L) | Acetic Acid | Deionized Water | Regulatory Level |
|---------|-------------|-------|---------------------------------|-------------|-----------------|-----------------|
| SiO$_2$ | 38.1        | Arsenic | 0.07 | 0.02 | 5.0 |
| Al$_2$O$_3$ | 18.4 | Cadmium | 0.00 | 0.00 | 1.0 |
| Fe$_2$O$_3$ | 5.93 | Lead | 0.00 | 0.00 | 5.0 |
| MnO | 0.02 | Zinc | 0.26 | 0.01 | — |
| MgO | 5.43 | Chromium | 0.33 | 0.03 | 5.0 |
| CaO | 22.9 | Manganese | 0.13 | 0.00 | — |
| Na$_2$O | 1.82 | Copper | 0.02 | 0.01 | — |
| K$_2$O | 0.56 | Selenium | 0.28 | 0.02 | 1.0 |
| TiO$_2$ | 1.39 | Iron | 0.01 | 0.01 | — |
| P$_2$O$_5$ | 1.37 | | | | |
| BaO | 0.69 | | | | |
| Cr$_2$O$_3$ | 0.01 | pH | 11.5 |
| SrO | 0.30 | CEC (meg/100 g) | 78 |
| Loss on ignition | 0.69 | Exchangeable Ca (mg/kg) | 14,300 |
| Total | 97.6 | Extractable P (mg/kg) | 13 |

Fly ash is strongly pozzolanic. When wetted, pure fly ash will form a relatively impermeable mass [24]. Thus, pure fly ash is inappropriate for filter media, and only mixtures of fly ash and clean sand with less than 5% fines were considered. With a final hydraulic conductivity of 9.1 mm/h after 28 days of saturation, construction sand mixed with 5% by weight fly ash possesses an adequate hydraulic conductivity to drain 0.3 m of ponded water within 33 h.

Zhang et al. [20] measured the phosphorus adsorption isotherms of several potential filter media by ASTM D 4646-03 with a 20:1 solution to solid ratio [25]. Five initial concentrations of 1, 3, 10, 20, and 30 mg/L P, as sodium phosphate in 0.01 mol/L KCl solution, were used. The 5% fly ash-construction sand mix adsorbed twice the phosphorus of the next best material, an expanded shale. Construction sand used in the mix originated from a sand and gravel pit excavating the aeolian Dougherty sand that was later processed to contain less than 5% fines (<0.05 mm). Table 2 lists laboratory measurements fits for Langmuir and Freundlich isotherms and field samples described in following sections. The mechanics of the adsorption are ill-defined. However, the mixture released negligible phosphorus in batch desorption tests, indicating that the adsorption is relatively irreversible. After these promising results, it was decided to use fly ash in the demonstration BRC.
Table 2. Langmuir and Freundlich phosphorus isotherm parameters obtained for initial screening, 2007 construction, and 2014 cores from four BRC [20].

| Material         | Langmuir | Freundlich |  |
|------------------|----------|------------|---|
|                  | \( q_m \) | \( B \)     | \( r^2 \) | \( K_F \) | \( n \) | \( r^2 \) |
|                  | (mg/kg)  | (L/kg)     |          | (L/kg)    |          |          |
| 5% Fly Ash-Sand  | 376      | 2.46       | 0.949    | 205       | 0.268    | 0.994    |
| Laboratory       |          |            |          |           |          |          |
| Screening Sample |          |            |          |           |          |          |
| 5% Fly Ash-Sand  | 385      | 2.89       | 0.998    | 203       | 0.295    | 0.981    |
| 2007 Construction|          |            |          |           |          |          |
| Sample           |          |            |          |           |          |          |
| BRC              |          |            |          |           |          |          |
| 2014 Core Sample |          |            |          |           |          |          |
| ECP              | 157      | 0.225      | 0.988    | 31.2      | 2.02     | 0.945    |
| GLA              | 383      | 0.031      | 0.971    | 19.4      | 1.49     | 0.986    |
| GHS              | 431      | 0.021      | 0.921    | 17.0      | 1.48     | 0.976    |
| SR               | 491      | 0.028      | 0.987    | 19.2      | 1.35     | 0.992    |

3. Bioretention Cells

3.1. Cells Sampled in 2014

Four of the BRC were sampled in 2014 and are listed in Table 3 along with their physical dimensions. Elm Creek Plaza (ECP) is at a busy strip mall and captures runoff from the parking lot, which would otherwise flow directly into a tributary of Grand Lake. The Grand Lake Association (GLA) is a visitor center that has the largest drainage area of the sites chosen for this project. Runoff comes from both a parking lot and the lawn. Grove High School (GHS) readily lent itself to cell construction. There was an existing swale transporting runoff from the staff parking lot to the storm water drain in the city right-of-way. The cell was designed to fit inside the swale. A private residence (SR) is a single family home with a property extending to the lake. The cell intercepts runoff from the property before entering the lake.

Table 3. BRC locations and physical dimensions for four cells sampled in 2014.

| BRC | Property Type-Location | Impervious Cover (%) | Drainage Area (ha) | Cell Area (m²) | Area Ratio (%) | Filter Volume (m³) | Total Volume (m³) | Average Depth (m) | Ponding Depth (m) | Ponded Runoff Depth (mm) |
|-----|------------------------|----------------------|-------------------|---------------|---------------|-------------------|-------------------|-------------------|-----------------|-----------------------|
|     | Commercial             | 36°34′44.8″ N 94°46′02.9″ W | 100               | 0.25          | 107           | 4.3               | 97.1              | 128               | 1.20            | 0.45                  | 20                    |
|     | Educational            | 36°35′55.6″ N 94°44′52.5″ W | 90                | 0.65          | 149           | 2.3               | 112               | 161               | 1.08            | 0.30                  | 7                     |
|     | Public                 | 36°37′27.4″ N 94°48′59.3″ W | 36                | 0.77          | 323           | 4.2               | 340               | 435               | 1.35            | 0.30                  | 13                    |
|     | Residential            | 36°38′58.2″ N 94°49′34.9″ W | 13                | 0.16          | 101           | 6.3               | 63.5              | 93                | 0.92             | 0.30                  | 19                    |

USDA soil mapping plot Eldorado silt loam (thermic Typic Paleudolls) at GLA and GHS, Shidler silty clay loam (thermic Lithic Haplustolls) at SR, and Razort silt loam (mesic Mollic Hapludalfs) at ECP [26]. However, all sites exhibited construction related to earth moving. Thus, natural soil profiles were not present.

3.2. Cell Design

In general, the designs for this project are consistent with the BRC guidelines set by Prince George’s County [27], Hunt and White [28], and the LID Center [29]. Figure 2 depicts...
a typical section of the BRC design for this project. Variations from the references cited include a 1:1 side slope for improved safety during construction, sand plugs for adequate infiltration through the top soil layer, fly ash-sand blend for the filter medium, and cover vegetation suitable for eastern Oklahoma. Construction for this project was formally bid through the Oklahoma Department of Central Services, requiring a complete Plans, Specifications, and Estimate package [1]. The funding agency’s highest priority for these cells was to provide a technology demonstration for the public. Sites were selected that had good public access, cooperative landowners, a variety of land uses, and an attractive installation. As such, cell sizing could not be held constant but had to be adjusted due to site limitations and landowner requests. Recommended cell surface areas for BRC range from 3 to 8% of the runoff area [28]. The four cells ranged from 2.3 to 6.3%. Three of the BRC had a ponding depth of 0.3 m, which produced a pond volume ranging from 7 to 19 mm of watershed first-flush runoff. The ponding depth for ECP was increased by 50% since its watershed is entirely pavement, which corresponded to 20 mm of watershed runoff. Available data on how much of the total contamination are contained in the first-flush is highly variable [30,31]. Nevertheless, monitoring in 2014–2015 presented later shows that the BRC ponds were able to catch almost all the normal rainfall events for the year.

The topsoil thickness in the BRC was 0.3 m, based on the advice of the landscape professional who did the vegetation design for the Grove Cells [32]. The available topsoil in Grove, Oklahoma, is a silty loam, with a hydraulic conductivity much less than 25 mm/h. Even blending equal parts sand and topsoil did not provide adequate hydraulic conductivity to ensure infiltration into the filter layer. Sand plugs that created a channel from the surface to the filter media were utilized. Small areas of clean sand were placed above the surface of the filter media to form the sand plugs. Topsoil was then backfilled around them, rendering forms unnecessary. Figure 3 shows the construction of drains and the filter material, and sand plug placement. Plugs totaling 25% of the cell surface were randomly placed with no two plugs touching. This area of sand plugs was sized to drain the cell within two days, based on one half of sand’s hydraulic conductivity, which would allow for clogging over time. The two-day limit on ponding prevents mosquito reproduction, which is important since several of the cells were at schools and public locations.

Total BRC depth was adjusted due to site topography and the distance the drain had to run to daylight. Average filter depth varied due to the 1:1 side slope and aesthetics adjustments to the cell shape. Filter volumes for the irregular cell shapes were calculated with a 3D model [33]. Average BRC filter depths ranged from 0.9 to 1.2 m, which is consistent with the transport calculations by Zhang et al. [20].
Surface inlet channel dimensions were calculated using a combination of the rational method and Manning’s equation. Since the drainage area size is limited to less than one hectare, the rational method was an acceptable means of calculating the expected surface runoff. A rainfall intensity of 91 mm/h was used that corresponds to a 50-year 1-h storm at Grove [34], which will provide a reasonable safeguard for these non-critical structures on small watersheds. The dimensionless runoff coefficient was assumed to be 0.95 for impermeable surfaces such as pavement and roofs. Manning’s equation was employed to size inlet and outlet channels. Slopes were estimated from the site topography. Depth of flow was set to 0.15 m and channel width calculated. An overflow bypass weir was placed on the back end of the cell. Values for weir height and total head above the weir were held constant at 0.3 m and 0.15 m, respectively, and the length of the weir sized using the broad-crested Weir equation. Chavez et al. [35] present additional design details and calculations.

BRC bottom drains are nominal 0.1 m (4”) diameter slotted corrugated polyethylene pipe with a filter fabric wrap. Within the cells, the drain pipe was spaced on a 1.5 to 2.7 m grid, with one or two pipes exiting the cell. Christianson et al. [36] utilizing agricultural field drainage relationships showed that this number of drain pipes was excessive. Even for the largest BRC, a single pipe down the middle would be adequate. Similarly, it was showed that a 50 mm (2”) pipe would be more than adequate for the flow. However, it was decided to over design this aspect of the BRC to ensure uniform flow through the filter media. Cell bottoms were not sealed since the native soils had low permeability and no significant leakage or inflow was expected. Stormwater monitoring, as presented later, showed that was not the case for at least two of the Grove BRC.

3.3. Cell Construction

The BRC construction, with one exception, followed normal procedures. The cell volume was excavated with frontend loaders. Evacuated spoil was used in grading berms and for the BRC top soil. Drain pipes were laid on the cell bottom and effluent exit pipes laid in level trenches until they day lighted to the natural grade. Filter material was backfilled, sand plugs and top soil placed, and the cells planted. The one unusual aspect of construction was mixing the fly ash on site. An unnamed alluvial construction sand with less than 5% fines and fly ash were combined in the field by two means shown in Figure 4. The first method involved mixing with heavy equipment before placement in the cell. A load of sand was deposited near the cell site and the required amount of fly ash was then mixed into the sand by repeatedly filling the bucket of a front end loader and pouring it back over the pile containing the sand and fly ash, until an even blend was achieved. The second method used a roto-tiller to mix media in 150 mm lifts inside the cell. While considerable effort was expended on both methods, sampling of the materials during
placement showed substantial and nearly equal variation in fly ash content throughout the filter layer [37]. Either method may be used in the future, but other options should be considered.

Figure 4. Mixing fly ash; (left) by front end loaders, (right) by rototiller.

BRC were planted from a list of native and nonnative species that were wet and dry tolerant, not N fixers, noninvasive, low maintenance, aesthetically pleasing, easily attainable, and replaceable. The list included trees, shrubs, flowering perennials, ornamental grasses, and rock accents. Property owners had the discretion to select final plantings from the approved list, and were responsible for maintenance. Thus, there soon developed a large variation between plant cover on the BRC [38].

To maintain landscaping aesthetics and to help retain moisture for the vegetation, a 50 mm hardwood mulch layer was applied over the topsoil/sand plug layer after planting the vegetation. Hardwood was used to minimize mulch loss due to floating when the cell pond has runoff. No compost was used in the cell due to potential phosphorus leaching. Figure 5 shows two completed BRC, soon after initial planting, while Figure 6 shows two cells in 2014 undergoing hydraulic testing [39].

Figure 5. Completed BRC; (left) GLA, (right) SR.
Figure 6. Mature BRC in 2014 ponded during hydraulic testing; (left) GLA, (right) GHS.

Figure 7 presents a plot of the BTC construction cost for all 10 cells as a function of the total cell volume. Costs include excavation, drains, filter sand, filter and topsoil placement, site grading, and construction erosion control [37]. Costs do not include design, contract supervision, flyash, or planting. The grove’s cell cost represents full outside contractor construction. The two OSU cells’ cost was lower due to the use of inhouse construction labor. It is expected that large scale projects would be more economical. Chavez et al. [37] reported planting cost ranging from $526 for the smallest cell to $4481 for the largest, GLA.

![BRC construction cost as a function of volume](image)

Figure 7. BRC construction cost as a function of volume [37].

After construction BRC maintenance was the responsibility of the landowners. GLA, GHS, and SP were well maintained. GLA and GHS sustained a landscaped appearance while SP was cultivated into a butterfly garden. ECP had no maintenance and quickly became overgrown with the planted and volunteer species. Nevertheless, plant cover did not appear to affect the BCE hydraulics.
Initial testing was performed on the BRC to support simulations of the flow hydraulics in the BRC [36,40]. With the simulated hydraulics, Chavez [41] performed stochastic, 3D, finite element modeling of phosphorus transport. A BRC similar in size to ECP was simulated for 144 years, with an influent concentration of 1 mg/L of phosphorus. That relatively high influent concentration was selected as a worst case scenario. Simulations using 75,000 elements examined three ranges of cell variability with 20 random realizations each. Figure 8 shows one simulation concentration distribution at 20 and 144 years, while Figure 9 presents the mean drain effluent concentration with time. Note that the phosphorus water quality standard of 0.035 mg/L would not be exceeded for 34 years. The earliest any simulation exceeded the standard was 17 years. The BRC were predicted to continue to reduce stormwater phosphorus for more than 100 years.

![Image of simulated adsorbed phosphorus concentrations](image1)

**Figure 8.** Simulated adsorbed phosphorus concentrations in fly ash-sand BRC; (left) at 20 years, (right) at 144 years [41].

![Image of mean effluent concentrations](image2)

**Figure 9.** Mean effluent concentrations from 20 simulations in 3-D model, for six sand plug cell with influent concentration of 1 mg/L [41].
4. 2014 Sampling and Monitoring

Quantification of the BRC performance is not a simple issue. There are three questions to address: (1) how much phosphorus is being retained now, (2) how much phosphorus has been retained over the seven years, and (3) how much more phosphorus will the BRC hold? The first question was addressed by stormwater sampling, the second was quantified by both stormwater sampling and field core sample extraction, while the third was predicted by laboratory adsorption measurements of field core samples.

4.1. Stormwater Flow and Phosphorus Sampling

Stormwater was monitored and sampled at three cells: ECP, GLA, and GHS in 2014 and 2015 [42]. Fourteen-bottle autosamplers with rain gauges collected BRC influent and drain samples. Continuous flow volumes were measured by Palmer–Bowlus flumes [43]. Storm events were defined by the successful collection of water samples using the automated samplers. The flumes triggered their respective samplers programed on an increasing time interval schedule. Rainfall events that did not produce runoff were ignored. Samplers were serviced within one day. Thus, sampled storms were separated by at least 24 h. The collected sampler bottles were proportionally combined based on the flume flow hydrograph to create a flow weighted composite sample. Unfiltered samples were analyzed by the Soil Water and Forage Analytical Laboratory, Oklahoma State University by inductively coupled plasma atomic emission spectroscopy (ICP-AES) for total phosphorus. The difference between the influent and drain sample provides the phosphorus concentration reduction. Mass fluxes for both influent and drains were calculated as a product of the event mean concentration and the total runoff volume measured during a runoff event. Table 4 presents the sampling results. The Wilcoxon Rank-Sum Test, a non-parametric analysis, was used to determine if the BRC treatment made a significant improvement on phosphorus reduction [44].

Table 4. Stormwater and drain mean T-P concentration, mean mass loading, number of storms sampled (n), and Wilcoxon Rank-Sum Test significance of difference between influent and drain (p).

| BRC | n  | T-P (mg/L) | Mean Mass Loading (g) | Reduction% | p   | Reduction% | p   |
|-----|----|------------|----------------------|-----------|-----|------------|-----|
|     |    | Influent   | Drain Effluent       |            |     | Influent   | Drain Effluent |
| ECP | 20 | 0.12       | 0.03                 | 75         | <0.05 | 3.25      | 0.22       | 93 | <0.05 |
| GHS | 9  | 0.15       | 0.05                 | 67         | <0.05 | 5.13      | 0.83       | 84 | <0.05 |
| GLA | 12 | 0.23       | 0.07                 | 68         | <0.05 | 12.65     | 6.22       | 51 | >0.05 |

At the GHS cell, ten sampled storm events occurred from September 2014 to September 2015. The mean storm size was 23 mm, while the median storm size was 19 mm. Event watershed runoff depths ranged from 2 mm to 80 mm. Three BRC overflow events occurred but were not recorded due to autosampler failures. A mean flow volume reduction of 13% was achieved. Total phosphorus effluent concentration was 67% lower than the influent, while T-P drain effluent mass was 84% lower than the influent mass.

At the ECP cell, 20 storm events were sampled storm events occurred from May 2014 to October 2015. Event watershed runoff depth ranged from 6 mm to 97 mm, the mean storm size was 26 mm, and the median storm size was 19 mm. No overflow occurred during the events. Drain flow for three storm events were not recorded due to autosampler failure. Both flow volume and phosphorus concentration were reduced. A flow volume reduction of 73% was achieved. This reduction is attributed to both evapotranspiration in the cell and seepage out of the unlined cell bottom. Total phosphorus effluent concentration was significantly reduced 75% from the influent, while T-P effluent mass was 93% lower than the influent mass.

At the GLA cell, 14 measureable storm events occurred from June 2014 to September 2015. Mean storm size was 37 mm, and the median storm size was 32 mm. Event watershed runoff depths ranged from 11 mm to 92 mm. One overflow event occurred during the event.
Flow in the GLA underdrain was higher than the inlet for most of the storms monitored due to groundwater seepage into the cell. The study area has low relief, so the source of the inflow was likely shallow saturated soil water from a large adjacent grassed field, which would have normally seeped into the adjacent lake, but was intercepted by the BRC. Flow from the underdrain was noticed at times with no precipitation or when there was no influent. Overall, underdrain flow volume was 12 times greater than influent during the monitoring period. However, even with this large seepage, T-P drain effluent concentration was 68% lower than the influent. Likewise, T-P drain effluent mass was 51% lower than the inlet influent mass, with a statistical significance of $p = 0.09$. While a complicated issue for this study, the cell is effectively treating water from other sources before it reaches Grand Lake. Thus, the unlined cell bottom is beneficial to reducing the lake’s phosphorus loading.

Of final note, Table 4 shows that the average drain effluent T-P concentrations ranged from 0.03 to 0.07 mg/L. This compares well with the Scenic Rivers Total Phosphorus Criterion of 0.037 mg/L [45]. However, Chavez’s [41] modeling with a much higher influent phosphorus load predicted that these concentrations could not be reached in the effluent for at least another 10 years.

4.2. Core Sampling Phosphorus Concentrations

Four cells, ECP, GLA, GHS, and SR, were selected for core sampling in 2014 [42]. Six, 38 mm cores were collected along the center line of each cell to a depth of 0.6 m, and it was deemed impractical to core the full depth of the BRC due to potential harm to the cell surface from the increased loads of the truck mounted core tool, and damage to the drains if pierced by the core tool. Visual examination of the cores did not show the sharp layering of construction. The top soil simply faded into the filter media. Apparently, planting, vegetation growth, maintenance, soil settlement, and the high infiltration blended the boundary of the top soil and filter material. Likewise, due to high organic matter, it was not possible to visually identify cores that sampled a surface sand plug versus the top soil. Thus, the 24 cores were simply sectioned into four, 0.15 m lengths. The upper section is assumed to reflect the original top soil, while the lower three are more representative of filter material.

Those 96 samples were subjected to three increasing vigorous extractions: water soluble by 20:1 water extraction (WS-P), weak acid by Mehlich-3 (M3-P), and total by EPA Method 3050 (T-P). M3-P is considered plant available phosphorus and an indicator of environmental availability, while Method 3050 is a total acid digestion which provides total elemental concentrations. Along with those subsamples, 32 samples of the original top soil and filter media collected and stored after the 2007 construction were subjected to identical procedures.

Table 5 and Figures 10–12 present the core phosphorus extraction results. Note that the analysis does not differentiate depth within the filter media since the initial samples were hand collected during construction and do not correspond to a specific position within that BRC. Not too surprisingly, a cursory examination of the graph scales shows clear differences between the extraction methods. The WS-P concentrations were less than 2 mg/kg, indicating that most phosphorus was strongly bound and would not be easily leached by rainwater. The M3-P concentrations were an order of magnitude higher at 10 to 40 mg/kg and showed the clearest increase from the near zero initial samples. Total phosphorus had by far the greatest magnitude, ranging from 170 to 440 mg/kg. It also had the smallest relative increase and significant variation between samples. However, it had an average increase of 17 to 83 mg/kg. Taken as a whole, these data show that the fly ash media is strongly retaining a significant mass of phosphorus.
Table 5. Mean and standard deviation of initial and final phosphorus concentrations by extraction method, and Tukey test significance of phosphorus increase in BRCs before and after seven years of operation ($p$).

| BRC  | Material  | Extraction | Initial (mg/kg) $n = 8$ | Final (mg/kg) $n = 20$ | Increase (mg/kg) | Increase Significance $p$ |
|------|-----------|------------|--------------------------|------------------------|------------------|---------------------------|
| ECP  | Top Soil  | WS-P       | 0.11 ± 0.1               | 1.4 ± 0.2              | 1.3              | 0.001                     |
|      |           | M3-P       | 1.7 ± 0.1                | 27.6 ± 4.6             | 25.9             | 0.001                     |
|      |           | T-P        | 225 ± 14                 | 308 ± 87               | 83               | >0.05                     |
|      | Filter Media | WS-P         | 0.1 ± 0.06              | 1 ± 0.3                | 0.9              | 0.001                     |
|      |           | M3-P       | 3.2 ± 0.2                | 7.6 ± 3.7              | 4.4              | 0.05                      |
|      |           | T-P        | 361 ± 110                | 440 ± 140              | 79               | >0.05                     |
| GHS  | Top Soil  | WS-P       | 0.2 ± 0.01               | 1.5 ± 0.3              | 1.3              | 0.01                      |
|      |           | M3-P       | 8 ± 0.07                 | 34.7 ± 7.7             | 26.7             | 0.01                      |
|      |           | T-P        | 265 ± 3.5                | 331 ± 115              | 66               | >0.05                     |
|      | Filter Media | WS-P       | 0.4 ± 0.05              | 0.8 ± 0.3              | 0.4              | 0.05                      |
|      |           | M3-P       | 5 ± 1.4                  | 19 ± 7.5               | 14               | 0.01                      |
|      |           | T-P        | 243 ± 19                 | 281 ± 33.7             | 38               | >0.05                     |
| GLA  | Top Soil  | WS-P       | 0.2 ± 0.01               | 2.7 ± 1.2              | 2.5              | 0.05                      |
|      |           | M3-P       | 10 ± 0.1                 | 30 ± 5                 | 20               | 0.01                      |
|      |           | T-P        | 276 ± 19                 | 290 ± 60.8             | 14               | >0.05                     |
|      | Filter Media | WS-P       | 0.3 ± 0.18              | 1 ± 0.8                | 0.7              | 0.05                      |
|      |           | M3-P       | 13 ± 3                   | 22.7 ± 8.6             | 9.7              | 0.05                      |
|      |           | T-P        | 196 ± 28                 | 223 ± 53               | 27               | >0.05                     |
| SR   | Top Soil  | WS-P       | 0.1 ± 0.01               | 5.7 ± 1.2              | 5.6              | 0.001                     |
|      |           | M3-P       | 5 ± 0.08                 | 39.8 ± 18.8            | 34.8             | 0.05                      |
|      |           | T-P        | 170 ± 17.7               | 312 ± 70               | 142              | >0.05                     |
|      | Filter Media | WS-P       | 0.2 ± 0.04              | 1 ± 0.7                | 0.8              | 0.05                      |
|      |           | M3-P       | 3.8 ± 0.3                | 12.7 ± 8               | 8.9              | 0.05                      |
|      |           | T-P        | 355 ± 129                | 372 ± 35               | 17               | >0.05                     |

Figure 10. WS-P mass concentrations in top soil and filter media in 2007 and 2014.
4.3. Annual Phosphorus Retention

The total annual phosphorus reduction was estimated by two methods. First, the measured stormwater concentrations were used for input to the Load Estimator (LOADEST) model [46]. LOADEST is a USGS program for estimating constituent loads in streams and rivers when only partial measurements are available. Given a time series of streamflow, and parameter concentration, LOADEST creates a linear regression model to predict the instantaneous load based on one or more sample input variables including discharge and concentration. LOADEST automatically creates several multiple regression models and selects the best model from those based on the lowest Akaike Information Criteria statistic. Table 7 presents the LOADEST predicted annual T-P reduction of 0.3, 0.27, and 0.41 kg/year at ECP, GHS, and GLA, respectively. These are relatively significant quantities when compared to the cells’ watershed areas.

Figure 10. WS-P mass concentrations in top soil and filter media in 2007 and 2014.

Figure 11. M3-P mass concentrations in top soil and filter media in 2007 and 2014.

The second method used the difference between the initial and final core phosphorus concentrations multiplied by the cell filter volume and dry density. Dry densities of 1400 kg/m³ and 1500 kg/m³ were used for the top soil and filter media, respectively. Phosphorus retention rates over the seven years of operation are presented in Table 7. The T-P trapped in the 0.6 m of the media sampled on the four BRCs were 0.4, 0.33, 0.51, and 0.6 kg/year at ECP, GHS, GLA, and SR, respectively. These values compare favorably to the LOADEST calculations. It is the opinion of the authors that, within the context of stormwater, they are the same.

Analysis of variance was performed using a Tukey test for the comparison of phosphorus accumulated over the seven years after construction. Both WS-P and M3-P showed statistically significant increases in phosphorus. Total phosphorus increased on all samples, but at a low significance level ($p > 0.05$). This is not surprising since the initial samples had high variance relative to the magnitude.

Table 6 presents the phosphorus concentrations by the three extraction methods as a function of depth in the 2014 cores. General transport theory would predict a near exponential reduction in the adsorbed solute concentrations with depth, which was not the case. However, there was a decreasing downward trend. An ANOVA using the General Linear Model [44] shows a linear trend for both WS-P and M3-P. Again, due to the large variance of the T-P samples, statistical significance was low, but the raw data show a trend. The lack of a stronger trend with depth is curious. One-dimensional modeling by Zhang et al. [20] and three-dimensional modeling by Chavez et al. [41] predicted that most
of the retained phosphorus would still be near the top of the BRC at the seven-year mark. However, both of those modeling efforts did not consider solute redistribution between infiltration events, evapotranspiration, or vegetation sequestration and removal. It appears that accurate prediction of the transport and the ultimate phosphorus retention within the BRC will require more complex modeling and/or longer term monitoring.

Table 6. Phosphorus concentration and standard deviation by extraction method and significance level of linear reduction with depth after seven years of operation (p).

| BRC | Extraction Concentration (mg/kg) | Depth (m) | Linear Trend |
|-----|----------------------------------|-----------|--------------|
|     |                                  | 0–0.15    | 0.15–0.30    | 0.30–0.45    | 0.45–0.60    | Significance p |
| ECP | WS-P 1.4 ± 0.2                   | 0.97 ± 0.2| 1 ± 0.3      | 1.2 ± 0.3    | 0.05         |
|     | M3-P 27.5 ± 4.6                 | 6.5 ± 0.8 | 6 ± 0.6      | 10 ± 7       | 0.001        |
|     | T-P 308 ± 87                    | 447 ± 99  | 469 ± 153    | 406 ± 196    | >0.05        |
| GHS | WS-P 1.5 ± 0.3                   | 0.67 ± 0.1| 0.9 ± 0.3    | 0.8 ± 0.4    | 0.001        |
|     | M3-P 34.6 ± 7.6                 | 15.4 ± 2.8| 16.6 ± 4.6   | 31.2 ± 6.8   | 0.001        |
|     | T-P 331 ± 114                   | 279 ± 50  | 282 ± 23     | 285 ± 9      | >0.05        |
| GLA | WS-P 2.6 ± 1.2                   | 0.7 ± 0.1 | 1.4 ± 1      | 1.4 ± 0.6    | 0.01         |
|     | M3-P 29 ± 5                     | 15 ± 1.8  | 26 ± 8       | 25 ± 9       | 0.01         |
|     | T-P 290 ± 60                    | 207 ± 33  | 255 ± 75     | 205 ± 30     | 0.05         |
| SR  | WS-P 5.0 ± 1.2                   | 1 ± 0.4   | 1 ± 0.6      | 1.2 ± 0.9    | 0.001        |
|     | M3-P 39.7 ± 18                  | 9.6 ± 3.5 | 7.5 ± 1.7    | 20.6 ± 10    | 0.001        |
|     | T-P 312 ± 170                   | 414 ± 267 | 387 ± 238    | 315 ± 230    | >0.05        |

4.3. Annual Phosphorus Retention

The total annual phosphorus reduction was estimated by two methods. First, the measured stormwater concentrations were used for input to the Load Estimator (LOADEST) model [46]. LOADEST is a USGS program for estimating constituent loads in streams and rivers when only partial measurements are available. Given a time series of streamflow, and parameter concentration, LOADEST creates a linear regression model to predict the instantaneous load based on one or more sample input variables including discharge and concentration. LOADEST automatically creates several multiple regression models and selects the best model from those based on the lowest Akaike Information Criteria statistic. Table 7 presents the LOADEST predicted annual T-P reduction of 0.3, 0.27, and 0.41 kg/year at ECP, GHS, and GLA, respectively. These are relatively significant quantities when compared to the cells’ watershed areas.

Table 7. Phosphorus mass retention rate within the BRC by core sampling and LOADEST modeling with water sampling results.

| BRC | Media     | Depth (m) | Phosphorus Retained by Extraction Method (kg/year) | Phosphorus Retained by LOADEST T-P (kg/year) |
|-----|-----------|-----------|-------------------------------------------------|-------------------------------------------|
|     |           |           | WS-P    | M3-P    | T-P    |                                 |
| ECP | Top Soil  | 0.15      | 0.002   | 0.05    | 0.16   | 0.30                           |
|     | Filter media | 0.45 | 0.006   | 0.03    | 0.24   |                                |
|     | Total     | 0.60      | 0.008   | 0.08    | 0.4    |                                |
| GHS | Top Soil  | 0.15      | 0.004   | 0.08    | 0.29   | 0.27                           |
|     | Filter media | 0.45 | 0.004   | 0.13    | 0.04   |                                |
|     | Total     | 0.60      | 0.008   | 0.21    | 0.33   |                                |
| GLA | Top Soil  | 0.15      | 0.012   | 0.09    | 0.07   | 0.41                           |
|     | Filter media | 0.45 | 0.01    | 0.14    | 0.44   |                                |
|     | Total     | 0.60      | 0.022   | 0.23    | 0.51   |                                |
| SR  | Top Soil  | 0.15      | 0.029   | 0.18    | 0.43   | Not Monitored                  |
|     | Filter media | 0.45 | 0.013   | 0.15    | 0.17   |                                |
|     | Total     | 0.60      | 0.042   | 0.33    | 0.60   |                                |
Figure 13. Phosphorus adsorption isotherms in aged BRC media and unweathered fly ash-sand. The ability of the fly ash-sand media to continue to retain phosphorus was quantified by measuring adsorption isotherms on samples of the 2014 core filter media and the unweathered initial material. Procedures were identical to those presented in Section 2. Figure 13 displays the actual measurements, while Table 2 presents the fitted Langmuir and Freundlich isotherm parameters. These data reflect adsorption above the phosphorus already retained on the media. Isotherm fits were good but substantially reduced in magnitude from the initial. The differences between the initial and 2014 filter media is a reflection of the phosphorus adsorption and any mineral changes during the seven years of BRC operation. The Langmuir fits produced roughly the same maximum sorption of 400 g/kg. However, the $B$ parameter, which is related to the binding energy, is reduced by two orders of magnitude from roughly 2.5 to 0.03 L/kg. This difference is interpreted to reflect the minerals with the highest binding energy becoming saturated with phosphorus or other ions.

4.4. Remaining Adsorption Potential of 2014 BRC Media

The ability of the fly ash-sand media to continue to retain phosphorus was quantified by measuring adsorption isotherms on samples of the 2014 core filter media and the unweathered initial material. Procedures were identical to those presented in Section 2. Figure 13 displays the actual measurements, while Table 2 presents the fitted Langmuir and Freundlich isotherm parameters. These data reflect adsorption above the phosphorus already retained on the media. Isotherm fits were good but substantially reduced in magnitude from the initial. The differences between the initial and 2014 filter media is a reflection of the phosphorus adsorption and any mineral changes during the seven years of BRC operation. The Langmuir fits produced roughly the same maximum sorption of 400 g/kg. However, the $B$ parameter, which is related to the binding energy, is reduced by two orders of magnitude from roughly 2.5 to 0.03 L/kg. This difference is interpreted to reflect the minerals with the highest binding energy becoming saturated with phosphorus or other ions.

The Freundlich $K_F$ parameter provides a convenient comparison of the potential adsorption. $K_F$ will equal the mass adsorption potential when the phosphorus solute concentration in the aqueous phase is 1 mg/L. Potential adsorption has been decreased an order of magnitude from roughly 200 to 20 mg/kg, or a 180 mg/kg reduction. This mass is greater than the 17 to 143 mg/kg of T-P extracted from the cores samples listed in Table 5.

There are one clear-cut and two potential causes for the difference between the initial and the 2014 core isotherms. First, obviously, the cores have adsorbed significate phosphorus that can be expected to lower the isotherms proportionally. Next, the initial and construction measurements were carried out quickly with samples that had never been previously wetted, while the cores had been wetted and aged for years. The pozzolanic mineralization with this fly ash is significant for at least 28 days after wetting [47]. Thus,
the initial isotherm may not be representative of aged material. Finally, the initial and construction isotherms were carried out with simple KCl solutions. Stormwater contains other ions, which, over the seven years of cell operation, may have taken adsorption sites in addition to those occupied by phosphorus. Nevertheless, the filter media continues to retain significant phosphorus as demonstrated by the water sampling. The confounding differences between the initial and aged samples make prediction of long-term filter phosphorus removal efficiency problematic without another round of sampling.

4.5. Observations on the Extraction Methods

Before ending, it is appropriate to comment on the different soil extraction methods used. It was anticipated and confirmed that WS-P would be low and only a fraction of the phosphorus in the filter. The main purpose of performing WS-P was to show that the phosphorus was strongly bound. Basic mass balance considerations indicate that T-P would be the best measure of phosphorus retention in the BRC. However, the high magnitude and variability of the initial and final sample clouds the estimate of performance. It was hoped that M3-P would provide a clearer picture of adsorption, as it had been used by others [48]. It did show an increase from near zero with time. Unfortunately, the magnitude of the increase was 2 to 18 times lower than the increase of T-P. It appears that, in these cells, most of the phosphorus is retained in forms not released by the M3-P extraction. Therefore, even with its high variability, the T-P extraction is the best for quantifying phosphorus retention.

While greatly dissimilar, the three extractions should not be considered conflicting. The correlation between T-P, M3-P and WS-P was determined using a Pearson correlation coefficient test with a significance level of \( \alpha = 0.05 \) chosen for the comparison [49]. Total phosphorus correlated with WS-P (\( r = -0.01 \)), and M3-P (\( r = -0.28 \)). Similarly, a correlation between M3-P and WS-P (\( r = 0.49 \)) was obtained. Thus, the three extractions should be considered complementary and essentially a measure of the spectrum of phosphorus adsorption.

Cursory mineralogy of the phosphorus in three of the initial 2007 samples was determined at the Brookhaven National Synchrotron Light Source II by X-ray absorption near edge structure analysis (XANES) [50] and listed in Table 8. Phosphorus was held as calcium, aluminum, and iron phosphates. The important point to note is the mineral variability between samples, which may explain some of the wide range of measured concentrations of the WS-P and M3-P extractions. These extraction procedures likely have different efficiency on the various minerals.

Table 8. XANES analysis of three initial samples taken at construction in SR cells; (a) 0 to 150 mm, (b,c) 300 to 450 mm separated by 2 m [50].

| Group            | Mineral (%) | Sample | a   | b   | c   |
|------------------|-------------|--------|-----|-----|-----|
| Calcium Phosphates | Brushite    |        | 13  | 20  |     |
|                  | Monetite    |        | 15  | 21  | 12  |
|                  | Hydroxyapatite |      | 19  | 21  | 28  |
|                  | b-tricalcium phosphate | | 7   | 10  | 6   |
|                  | Octacalcium phosphate | | 8   | 11  | 13  |
| Aluminum Phosphates | Variscite |        | 9   | 9   |     |
|                  | Al Oxide Sorbed PO4 | | 9   |     | 12  |
| Iron Phosphates  | Strengite   |        | 11  |     |     |
|                  | Amorphous Fe Phosphate | | 8   | 8   |     |
|                  | Fe Oxide Sorbed PO4 | | 11  | 13  |     |
| Phytic Acid      |             |        |     |     | 5   |
| R-Factor         |             |        | 0.0204 | 0.0666 | 0.0207 |
The ultimate inference from these results is that accurately quantifying phosphorus retention using field filter media samples is challenging. Core sampling aged cells has a great advantage in labor and expense compared to continuous influent and effluent monitoring. However, sample concentration variability weakens most statistical tests. It is recommended that future research use all three methods used here to address variation. However, it may be appropriate to explore the use of an extraction between M3-P and T-P in strength in the hope of reducing sample variability.

5. Other Research on These BRC

Several other aspects of these cells have been examined. Zhang et al. [19] performed batch adsorption of heavy metal retention on fly ash, fly ash and sand mixtures, and other materials. They also carried out bench scale column transport experiments with copper, lead, and zinc. These results were used as inputs to a one-dimensional leaching model. This model predicted that the fly ash-sand mix would retain moderate influent concentrations of those metals for hundreds of years. Chavez et al. [40] performed three-dimensional modeling of a BRC with sand plugs and the measured fly ash sample variability measured during the construction. They found that the spatial variability in the flow and adsorption present in the cells would not seriously impact the cell performance. Christianson et al. [36] performed hydraulic testing on the GLA and GHS cells, using fire hydrant flow to simulate storms. These results were compared to a one-dimensional unsaturated flow model for both wet and dry conditions. After calibration, model flow volumes matched measurements, but the model hydrographs did not display the tailing of the measurements. Chavez et al. [37] provide details of the design, construction, and lessons learned during these projects. After examining one cell failure, they recommend specific guidance for future construction. Coffman et al. [38] quantified plant survival and performance in the Grove BRC, and recommended two plant palettes for future consideration. Kandel [49], in parallel to the phosphorus measurements of Kandel et al. [49], quantified copper, lead, and zinc retention in the BRC. He found that metal concentrations significantly increase in the BRC. No conclusions were made on effluent reductions in copper and lead since most measurements were below detection. However, total zinc mass was shown to be reduced 43 to 88%. McLemore [39] repeated the hydraulic experiments of Christianson et al. [36]. He found that, in the continuous flooding test, both BRC experienced a reduction in the drain flow of about one-half from their earlier rates. However, both cells were still meeting hydraulic design standards and providing pollution retention. Youngblood et al. [51] in concert with Vogel et al. [4] quantified E. coli, enterococci and coliphage effluent removal in three of these BRC. They found that, while removal was highly variable, fly ash amended bioretention in these cells performed 49% better than those with a pure sand filter media layer reported in the literature.

Two of the original fly ash BRC are part of an environmental research and education program in partnership with the Oklahoma State University Botanic Gardens in Stillwater, OK. One cell receives runoff from a short stretch of roadway serving as an entrance into the botanic gardens and a nearby gravel parking lot, respectively, and is experimentally paired with a section of permeable pavement. The second cell is paired with an equivalent cell that does not have the fly ash amendment. In an exploratory study, over six storm events, T-P was low in both influent and drain effluent, probably due to adsorption in the parking lot gravel [16]. However, T-P in the fly ash drain was reduced from the influent by 69%, while the pure sand removed 54%.

6. Summary and Conclusions

This research has demonstrated the potential for using fly ash as an additive in BRC. Average drain effluent T-P concentrations on the three cells sampled ranged from 0.03 to 0.07 mg/L. This compares well with the Scenic Rivers Total Phosphorus Criterion of 0.037 mg/L. Drain effluent T-P mass was reduced 51 to 93% compared to the stormwater influent over the year of monitoring. Performance is made even more noteworthy when
it was observed in testing and monitoring that the cell design was able to filter almost all surface runoff. Core sampling on four cells showed T-P retention of 0.33 to 0.60 kg/year over their seven years of operation, which correlates to the 0.27 to 0.41 kg/year estimated from water sampling in the seventh year. These BRC are clearly performing at a good level of phosphorus removal. In addition, other research has shown improved heavy metal and microbe retention. All lab, modeling, and field results justify expanded use of fly ash amendments in stormwater systems.

The design of these cells with the sand plugs to improve infiltration and prevent prolonged surface ponding has proven successful. After seven years of vegetation growth and filtering, the cells still maintain at least one-half of their initial filter rate. Their hydraulic performance should be adequate for the foreseeable future. The only recommendation for construction changes is to use a better method to mix the fly ash and sand.

Quantifying the long-term performance of these BRC will need additional research. Specifically, the measure phosphorus adsorption in the media and concentrations in the effluent was not well predicted by laboratory and computer modeling. Initial isotherm measurements used in both simple 1D modeling and complex 3D modeling predicted that, at seven years, the effluent T-P would be well below the 0.037 mg/L criterion. Likewise, the modeling also predicted that phosphorus would still be concentrated near the cell top. However, coring showed it more uniformly distributed with only a small decreasing trend to the bottom. It is suspected that there are two causes for the inability of the models to better fit the actual cell mechanics. First, phosphorus isotherms of the aged core material indicate loss of adsorption capacity exceeding the mass retained over the seven years of operations. The most likely cause of the decrease is a change in the fly ash-sand filter mineralogy as it aged. However, this decrease could also be the result of adsorption site competition from other stormwater solutes. Second, modeling may require simulation of solute redistribution between infiltration events, evapotranspiration, and/or vegetation sequestration and removal. These added processes could increase modeling complexity by an order of magnitude and necessitate additional field measurement of input parameters.

Core sampling is in the authors’ opinion the gold standard for measuring long-term pollutant retention. It is not easy to question its foundation in simple mass conservation. Likewise, it is much simpler to take a core than to install and maintain multiple stormwater samplers for a year or more. However, when applied to filter materials, the ability to distinguish between initial and adsorbed phosphorus makes the selection of the extraction process problematic. None of the three extractions used here were ideal, but each provided a useful measure. WS-P showed that most of the adsorbed phosphorus was strongly bound—a practical, if not a somewhat obvious, result. M3-P gave the clearest indication of the difference between the initial and seven year samples, but it appeared to measure one-half or less of the phosphorus adsorbed from the stormwater. Average T-P values compared well with the estimate of annual stormwater retention; however, the sample variability greatly weakens the interpretation of the results. A better extraction method is needed for any future core sampling program. Until that occurs, it is recommended that all three of these extractions be carried out.

It has been seven years since the 2014 sampling. A new round of laboratory measurements, modeling, and field monitoring should provide a stronger assessment of the fly-ash BRC long-term performance. If conducted, the procedures used here, incorporating the recommendations for improvement, should be adequate. However, the phosphorus adsorption processes on the weathered fly ash-sand media should be given careful consideration. Extending the fly ash research to other applications is reasonable. In particular, granulized fly ash filters may produce another effective design option.

With 12 years of design, construction, modeling, and testing, the fly ash BRC have one of the best, if not the best, documentation and quantification of any stormwater filter demonstration. However, the nature and limitations of piecing together a long-term research project from a range of agencies prevented better integration. In addition,
of course, the researcher’s most common hindsight lament is magnified by the project duration, “If only we knew the results at the start of the project . . . ”.

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